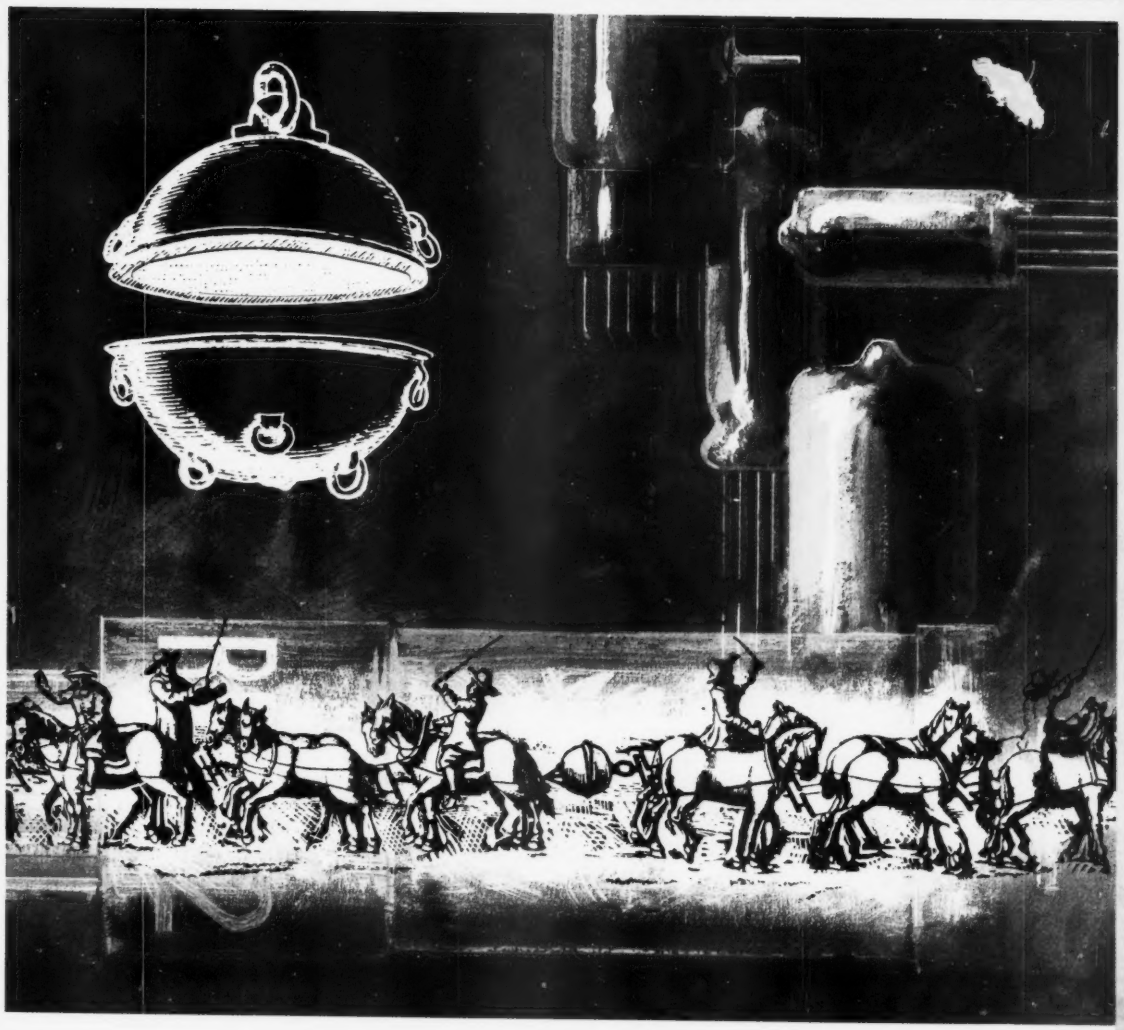
RAYTHEON

ELECTRONIC PROGRESS

May
June 1959



In this issue: VACUUM TECHNOLOGY

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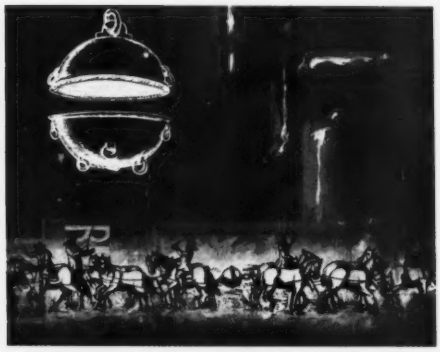

Vacuum technology has progressed considerably since 1654 when Otto Von Guericke invented the first air pump and conducted his famous experiment with the Magdeburg hemispheres. Klystrons, receiving tubes and transmitting tubes are just a few of the many modern devices which rely on advanced vacuum techniques.

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Inventions

Congratulations to the following persons for their valuable contributions to Raytheon's portfolio of inventions:

Name	*Field of Invention*
COLIN BOWNESS	Microwave Amplitude Modulator
WILLIAM BROWN	Space Vehicle
WILLIAM CAITHNESS R. P. TUINILA	Cathode Poisoning Prevention
MICHAEL DANILOFF	Analog Program Computer
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FRANCIS O'HARA HOWARD SCHARFMAN	Microwave Ferrite Serrodyne
PETER RIZZI	Guide Ferrite Generator
HOWARD SCHARFMAN	Ferrite Device
FRED YOUNGREN	Radome Design

Contents

Infrared Guidance of Homing Missiles	*W. J. Haywood, Jr.*	1
Vacuum Technology	*W. T. Eriksen*	8
The Detection of Microleaks	*I. P. Fish*	11
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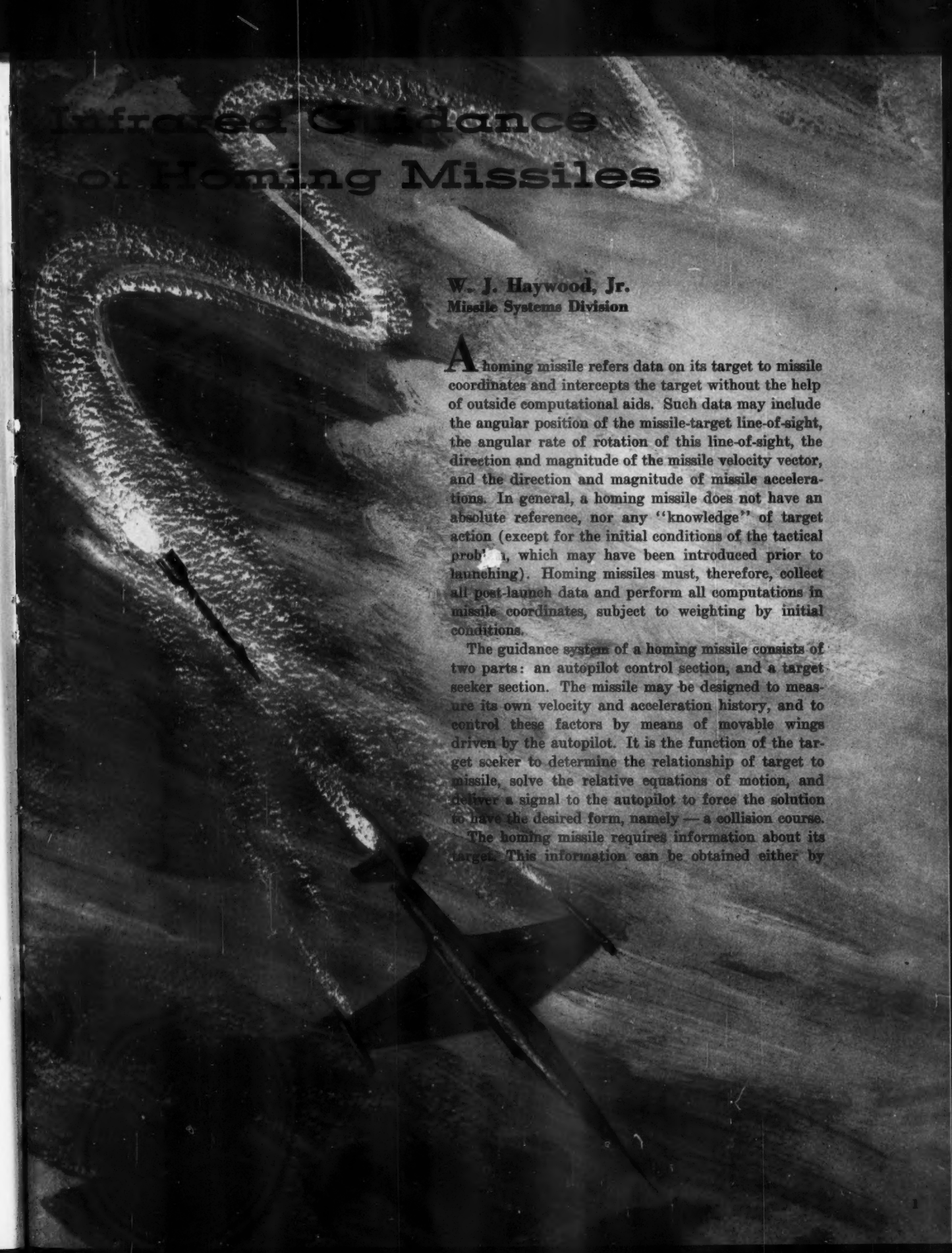
Radar Data Processing	*R. L. Wyckoff*	17
Publications and Papers		20



Infrared Guidance of Homing Missiles

W. J. Haywood, Jr.
Missile Systems Division

A homing missile refers data on its target to missile coordinates and intercepts the target without the help of outside computational aids. Such data may include the angular position of the missile-target line-of-sight, the angular rate of rotation of this line-of-sight, the direction and magnitude of the missile velocity vector, and the direction and magnitude of missile accelerations. In general, a homing missile does not have an absolute reference, nor any "knowledge" of target action (except for the initial conditions of the tactical problem, which may have been introduced prior to launching). Homing missiles must, therefore, collect all post-launch data and perform all computations in missile coordinates, subject to weighting by initial conditions.

The guidance system of a homing missile consists of two parts: an autopilot control section, and a target seeker section. The missile may be designed to measure its own velocity and acceleration history, and to control these factors by means of movable wings driven by the autopilot. It is the function of the target seeker to determine the relationship of target to missile, solve the relative equations of motion, and deliver a signal to the autopilot to force the solution to have the desired form, namely — a collision course.

The homing missile requires information about its target. This information can be obtained either by

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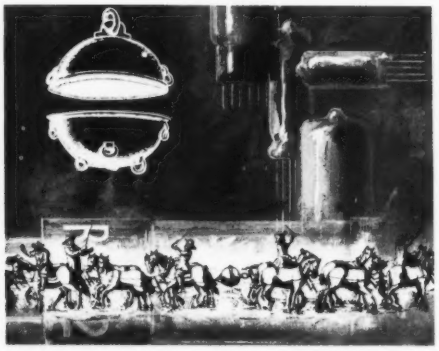

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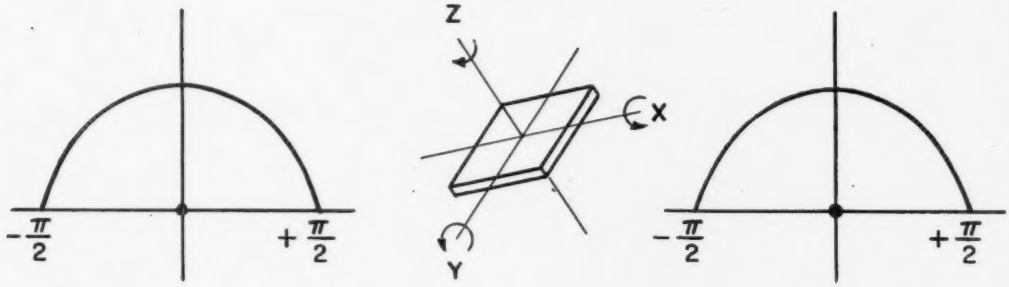


Figure 2

actively illuminating the target and sensing its motions by means of reflected energy, or by detecting the target's self-radiation (from its own power source). This latter technique allows a passive detection scheme to be used, thereby avoiding the problem of alerting the enemy.

The infrared energy radiated by military targets provides one method of passive missile guidance. It is of interest to note that radiant IR energy is electromagnetic in nature, and thus travels at the speed of light; while heat energy carried by conduction travels at a snail's pace, literally. Therefore, in spite of the huge quantity of heat dumped overboard by internal combustion engines in the form of hot combustion products, only the small fraction radiated away is available at a distance for the detection and tracking of these engines.

The heart of an IR seeker is the detector which serves to detect sources of IR radiation. It is a device which converts photons of electromagnetic energy into electrons in an electrical circuit by one of two mechanisms. Either there is a direct energy exchange within the detector material, freeing bound electrons, or there is a resistance change in the material, modulating a current flow. Semiconductor materials exhibit the first type response, photo-resistors and bolometers exhibit the second. In any event, there is a net energy loss in the process since not all quanta are captured or used to produce signals. Figure 1 shows a typical detection system.

All of these devices have noise thresholds. In a well designed system, the detector noise is well above that produced by the associated electronics. This is necessary to make full use of detector sensitivity. This is not difficult with most currently available detector types, although one should note that some detectors have very high or very low input impedances, which are difficult to work with. The amplifier simply raises the signal level to that required for efficient computation, without adding additional noise. In real systems, the computer-amplifier blocks may be difficult to separate.

The computer must operate on the complex signal from the detector-amplifier chain and make decisions as to the line-of-sight angles, and the angular rates of rotation of the line-of-sight, in whatever type of coordinate system has been chosen. It will become evident that this task is relatively simple in theory, although quite difficult to implement accurately at high speed. For the sake of this discussion, we decide that our missile knows which way is "up"; hence we can use simple cartesian coordinates for our measurements. Note that it is quite possible to solve all the problems for a missile which is free to roll on its own axis, and which therefore has no "up" reference, but the dynamics of the problem (which are a strong function of roll rate and undesirable couplings between control axes) creep in to perturb the system.

Relative to the problem of sensing direction in space of the target, there are many ways in which the direction of arrival of electromagnetic energy may be determined. The simplest of these is to expose a detector having a flat plane surface of area A to the incident energy. If this detector is slowly rotated around two axes through the plane, until the signal is a maximum around each axis, it can be seen that the detector is perpendicular to the direction of arrival of the incident energy. That this is true may be seen by looking at Figure 2. If we assume that the direction of arrival of energy is perpendicular to the Y-axis in the detector, which is then rotated around the X-axis from minus $\pi/2$ through 0 to plus $\pi/2$ with re-

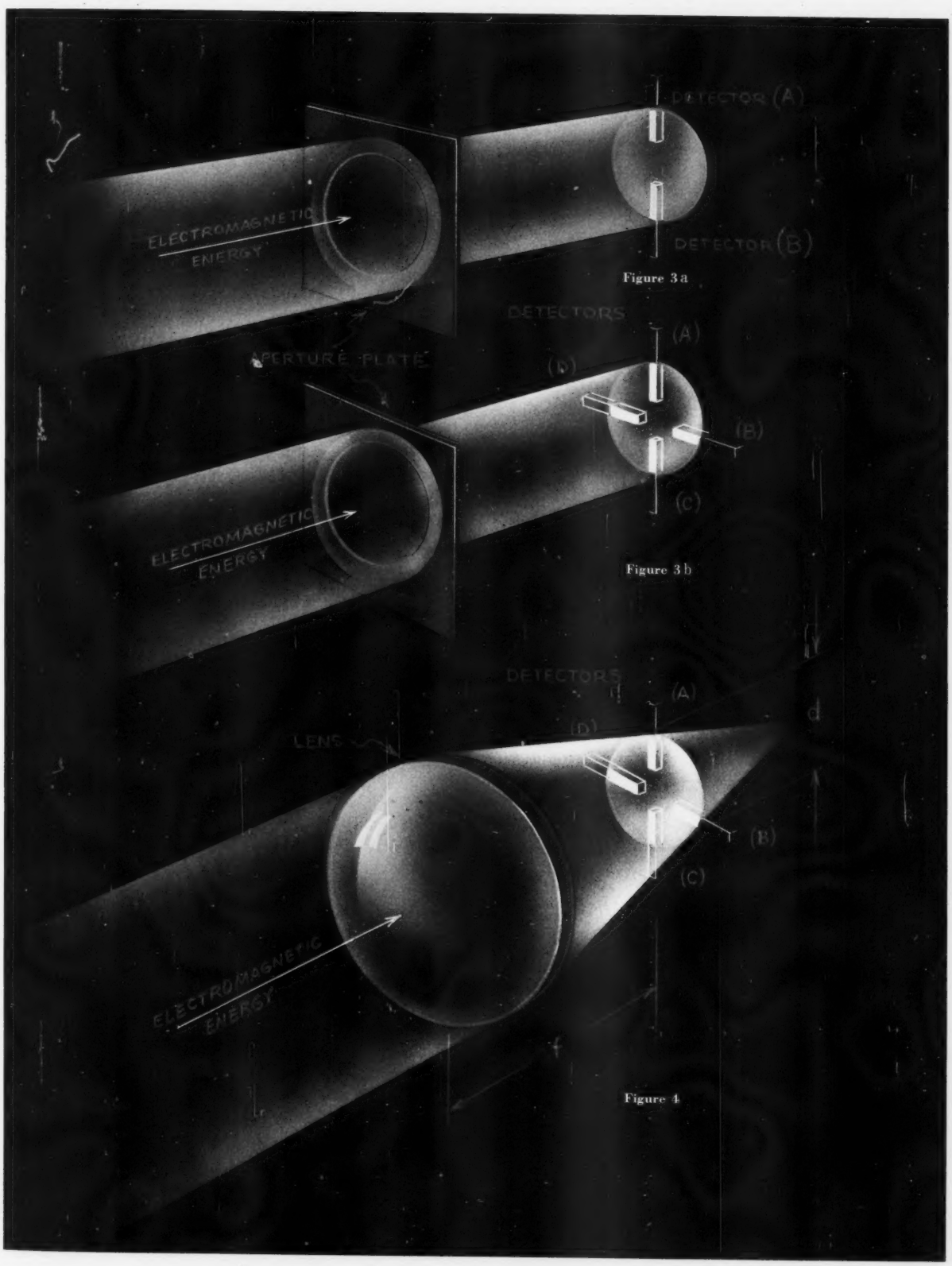
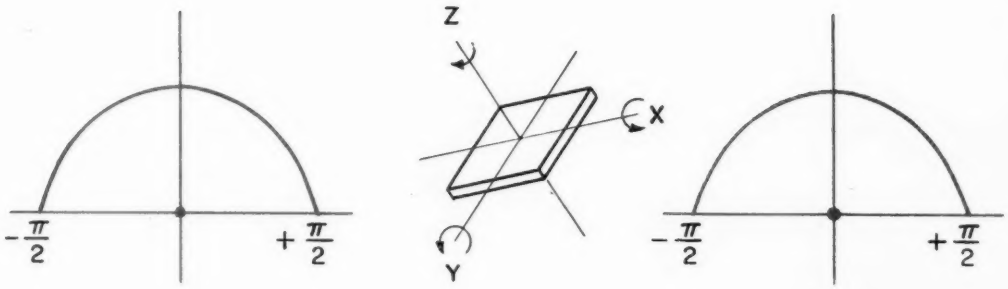


Figure 3a

Figure 3b

Figure 4

Figure 1



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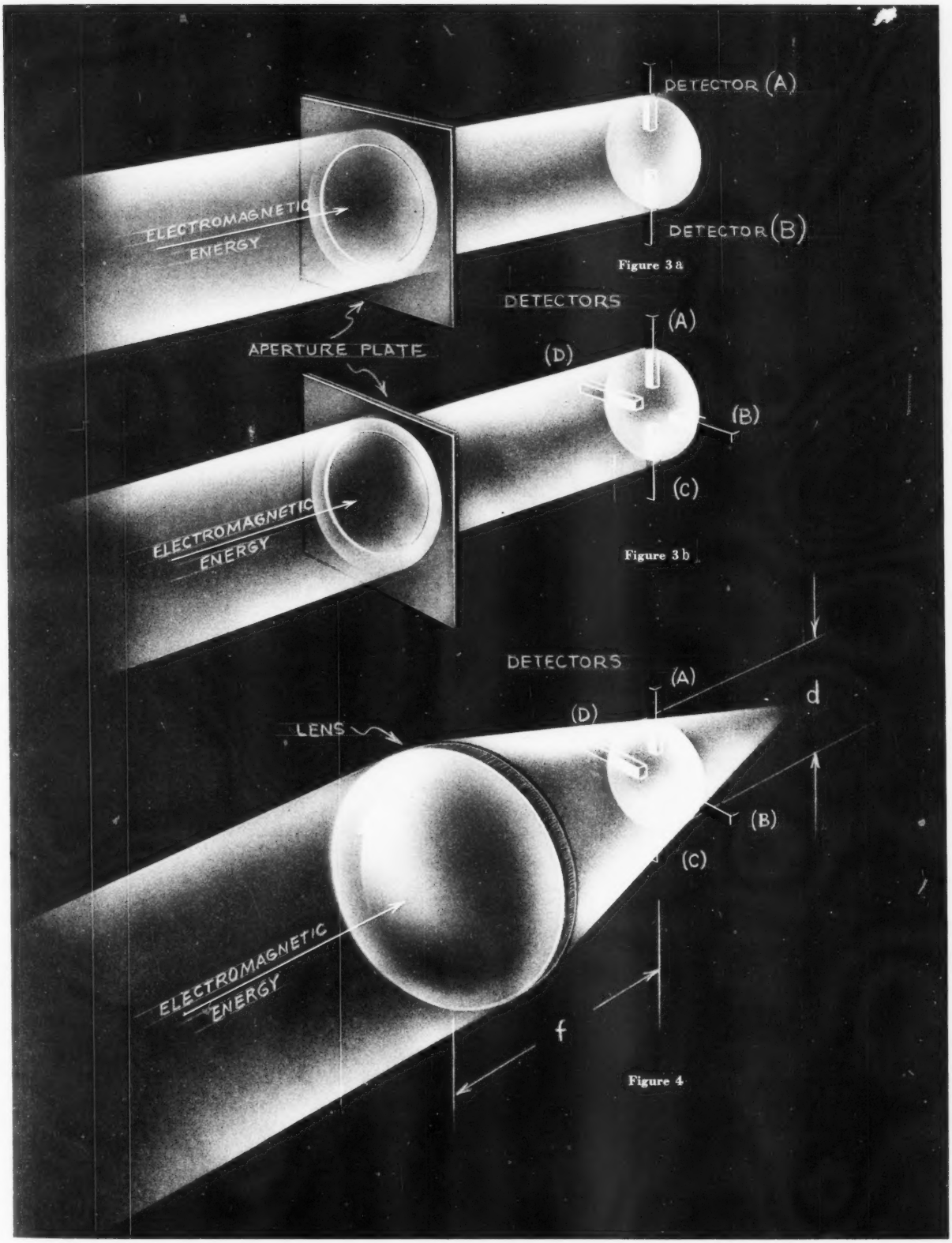

Figure 3a

Figure 3b

Figure 4

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This system constitutes a very simple directional device. It is, of course, very insensitive to change near the maxima. It is most sensitive near plus or minus $\pi/2$, where the response is quite small.

There are many problems in the operation of such a simple direction-sensing device. For example, it would be quite difficult to separate rotation through the X- and Y-axes. The detector has no auxiliary optics and is relatively insensitive to incident radiation.

A simpler method, making use of more than one detector unit, is shown in Figure 3A. Here a pencil of incoming energy is incident on an aperture plate separated by a small distance from two detectors which are contiguous to one another. If the energy divides equally between the two detectors, the output signal from them will be equal. On the other hand, if the line-of-sight to the target rotates slightly in such a way that one of the detectors receives more of the incident energy than the other, the output signals would be unbalanced so as to indicate the direction of rotation of the line-of-sight departure from zero incidence.

An extension of this technique can be visualized whereby four detectors are used to determine the motion of the line-of-sight with respect to the aperture plate in two directions, X and Y. The signals from the detectors may be made proportional to the departure of zero incidence angle line-of-sight. Thus, two signals are available to the designer. Figure 3B shows a system utilizing four detectors (A, B, C and D) located around the edges of a beam of energy defined by an aperture plate.

It is, of course, obvious that none of the schemes discussed in Figure 2 or Figure 3 can have a sensitivity greater than that of the elementary detector unit. In fact, the sensitivity of the schemes shown in Figure 3, is somewhat less than the maximum sensitivity of the detector units because a portion of the detector must not receive energy in order for a change to be sensed.

Extension of the technique shown in Figure 3 allows the use of a simple optical collecting system, as shown in Figure 4. Here we see a simple collecting lens whose total area for reception of incident energy is considerably larger than that of the four detectors A, B, C and D. It is used to focus the energy on a smaller area. Since all the incident flux on the left hand surface of the collecting lens passes through the circle incident at the four detectors, the flux density on the detectors is increased. There is, therefore, net optical gain. By proper selection of the material of the lens and the shape and disposition of the detectors, a quite satisfactory directional sensing system can be built, composed of the five simple elements shown in Figure 4.

The addition of optical gain in the simple systems shown in Figure 2 and Figure 3 is not without its cost. In optics, it is approximately true that the product of the gain and the field of view is a constant, as the gain-bandwidth product is constant in an electronic system. The simple directional scheme in Figure 2 had an extremely wide field of view, approximately π steradians. It also had low gain in the sense that the detector worked unaided to collect energy. The simple scheme in Figure 4, on the other hand, has a gain which is given by Equation (1). Here the optical gain is simply equal to the surface area of the lens divided by the sum of the useful areas of the detectors. The field of view of the simple system in Figure 4 is given by Equation (2). Notice that field of view is approximately given by the image size divided by focal length, for small fields. It is, in other words, the angle subtended by the detectors at the lens. Notice also that an increase in gain obtained by decreasing the size of the detectors produces a decrease in the field of view.

Unfortunately, it is also true that the sensitivity of detectors is not independent of their physical size. If Equation (1) is multiplied by the square of Equation (2), it can be seen that the gain-field-of-view-squared product is in fact a constant (the area of the lens divided by its focal length squared) and is equal [as shown in Equation (3)] to one over the F-number squared of the system. The F-number of the system is defined as the focal ratio. It is the focal length of the lens divided by its optical diameter. Since it is desirable to maximize the gain and to let the field of view have some moderate size dictated by the tactical situation, it would seem desirable to decrease the F-number to as small a value as is reasonable.

Intensity of the signal will vary with changes in direction of the line-of-sight. Any IR missile directional system which makes use of these variations, however, will also be affected by the change in intensity produced by the decreasing range as the missile homes on its target. To resolve this dilemma, it is necessary that the two rates of change be separated in the frequency spectrum. One way to do this is to cause the amplitude change due to change in line-of-

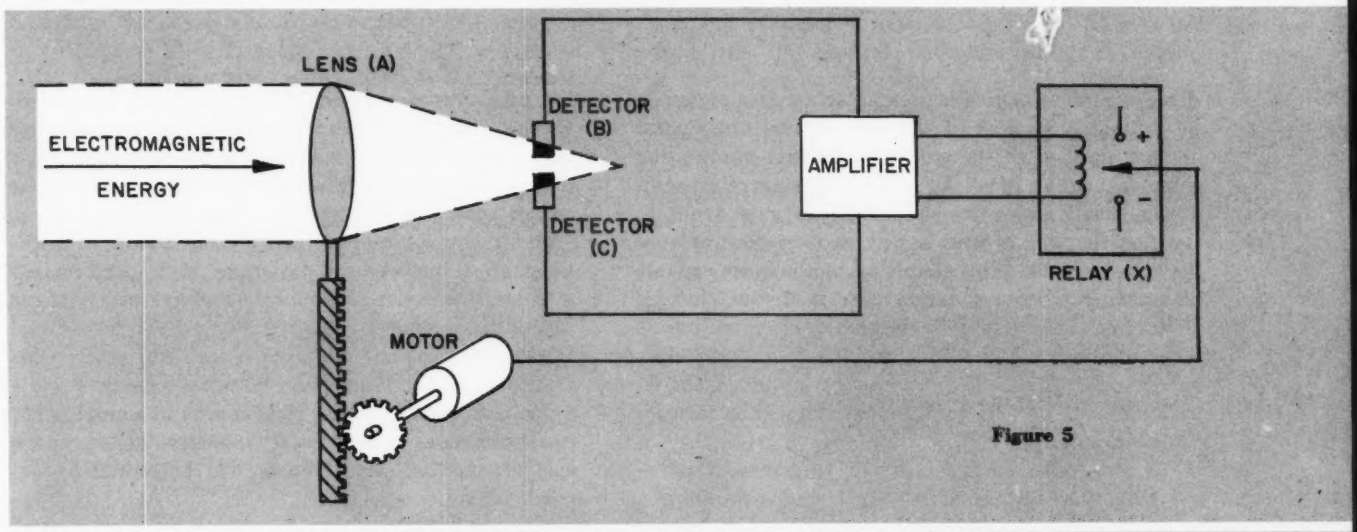

Figure 5

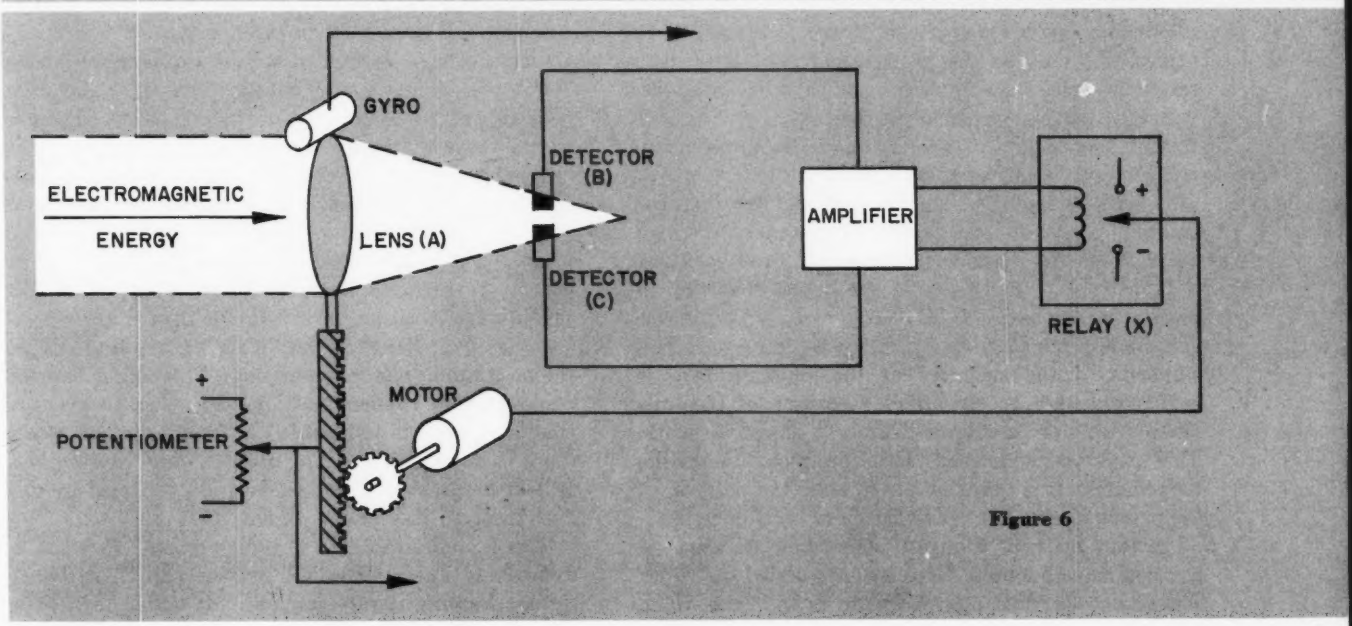

Figure 6

sight to be very much faster than that produced by closure of the range. All missiles which make use of variation in intensity to detect changes in direction are subject to this type problem. It is a most difficult problem to resolve, requiring careful analytical study of the kinematics of the tactical situation and careful analytical design of the dynamics of the target-seeker tracking system.

The simple optical systems and detection schemes illustrated all suffer from one fault. Only as long as the detector is actually in the field-of-view will the system give an output which can be used to describe the position and motion of the target. The field-of-view of practical systems is quite small, in the order of a couple of degrees wide. Since the target may occupy virtually any position in space, it would be quite difficult to keep track of a rapidly moving target with such a simple system if it had to be manually pointed and continuously kept in line with the target.

One way around this difficulty is to cause the output signal of the detector to keep the head pointed in the direction of the target. This self-tracking operation can be had by analyzing the detector signal, determining the direction of the target, and using the electrical signal proportional to direction to actuate a simple servomechanism which rotates the optical head in the correct direction.

Figure 5 shows a simple self-tracking optical detection system. Here the lens A focusses energy on cells B and C. Motion of the line-of-sight in an up-

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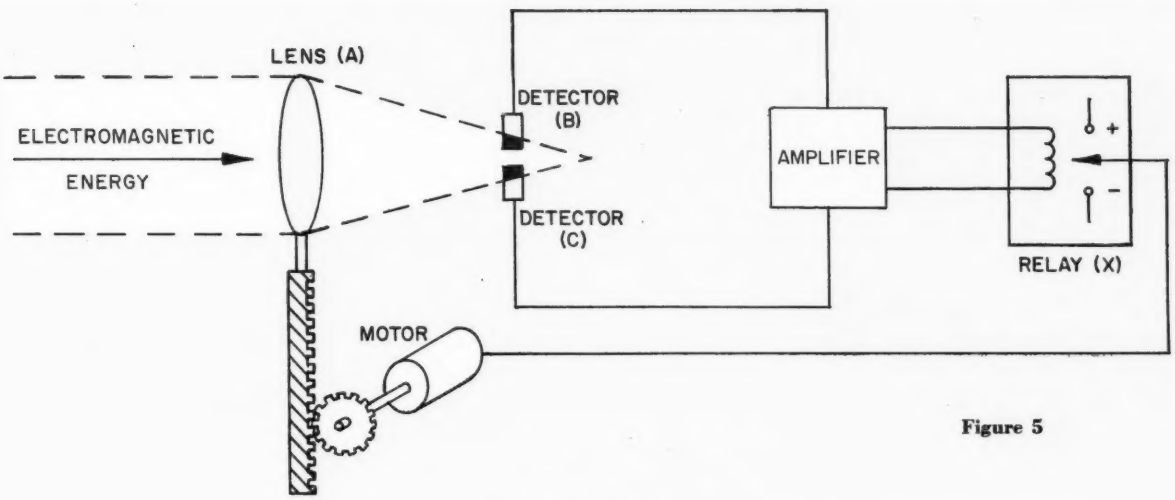

Figure 5

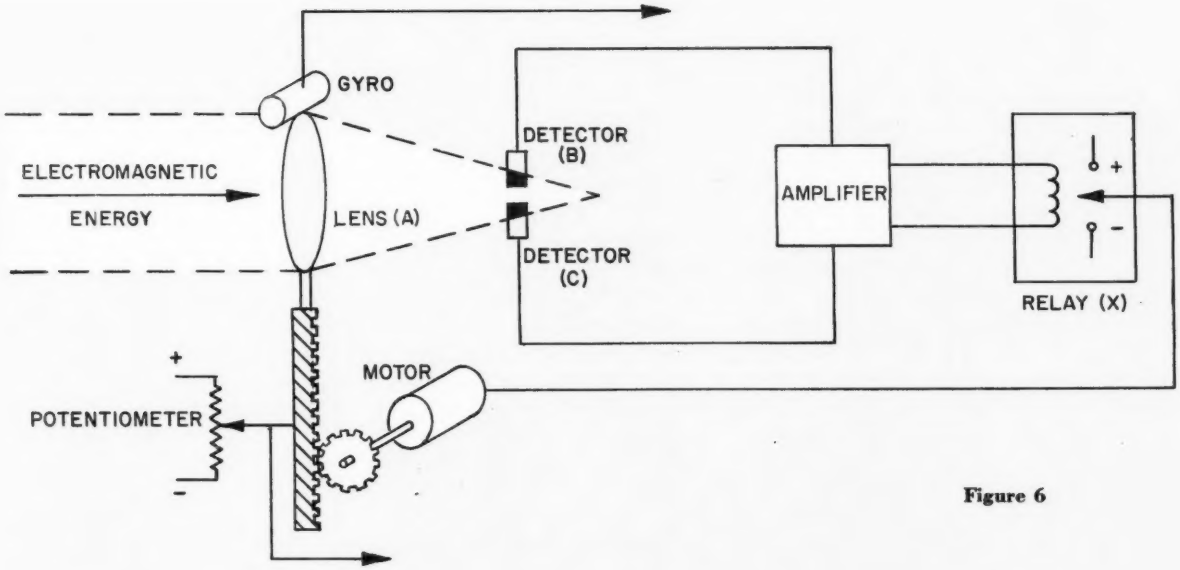

Figure 6

sight to be very much faster than that produced by closure of the range. All missiles which make use of variation in intensity to detect changes in direction are subject to this type problem. It is a most difficult problem to resolve, requiring careful analytical study of the kinematics of the tactical situation and careful analytical design of the dynamics of the target-seeker tracking system.

The simple optical systems and detection schemes illustrated all suffer from one fault. Only as long as the detector is actually in the field-of-view will the system give an output which can be used to describe the position and motion of the target. The field-of-view of practical systems is quite small, in the order of a couple of degrees wide. Since the target may occupy virtually any position in space, it would be quite difficult to keep track of a rapidly moving target with such a simple system if it had to be manually pointed and continuously kept in line with the target.

One way around this difficulty is to cause the output signal of the detector to keep the head pointed in the direction of the target. This self-tracking operation can be had by analyzing the detector signal, determining the direction of the target, and using the electrical signal proportional to direction to actuate a simple servomechanism which rotates the optical head in the correct direction.

Figure 5 shows a simple self-tracking optical detection system. Here the lens A focusses energy on cells B and C. Motion of the line-of-sight in an up-

down direction causes a greater or smaller signal to be generated by each of the cells. These unbalanced signals, applied to the amplifier, actuate a reversing relay (shown as Block X). The reversing relay actuates a small motor which drives the gear train to position the lens in such a way as to restore balance between the cells. This simple system is quite capable of tracking a moving target over moderate changes of the line-of-sight in a single plane. By extension of such techniques to two axes, using two motors (each independent of the other) and two amplifier chains with two sets of detectors, two-axis tracking may be obtained.

We now have the capability of pointing an infrared detection system at a target and causing the system to track the target automatically. This tracking capability of the system, once positioned on a target, implies that the response of the closed loop tracking system of Figure 5 must be sufficiently fast to keep a moving target in the field-of-view. This one requirement is the entire crux of the design of infrared homing target seekers.

It will be noticed that by making the infrared tracker a closed loop device, we have substituted changes in the position of the principle lens for changes in the signal out of the detector as the direction of the line-of-sight changes. In other words, a mechanical motion has been produced which corresponds, if the accuracy of the tracking loop is sufficiently high, to the angular position of the line-of-sight and to its angular rate of change in space. This physical motion has been produced in missile coordinates. It is quite simple to sense the position of the principal lens but somewhat more difficult to sense its rate of motion. Figure 6 shows how its physical position may be sensed. Here we have added the wiper arm of an electrical potentiometer on the rack which is driven by the control system motor. The wiper arm moves across a resistance element which has a potential between its terminals. A voltage proportional to the position of the rack will, therefore, appear at the wiper arm.

It is possible in theory to differentiate this voltage and obtain a second voltage which is proportional to the rate of motion of the wiper arm along the potentiometer. In practice, such a differentiation technique is quite difficult because potentiometers are noisy devices in general. Differentiation increases the noise out of such a source very rapidly. For this reason, and for several reasons which have to do with the kinematics involved in designing high performance missiles, it is easier to mount a small gyroscope on the top of the primary lens (see Figure 6). The signal from this gyroscope will be proportional to the rate of motion of the head while tracking a target. Since gyroscopes can only sense motion around a single axis, two gyroscopes are necessary to drive the primary lens around two axes. These will be mounted perpendicularly to each other.

We now have the basic closed-loop tracking system (shown in Figure 5) with the addition of a position-indicating device and two velocity-indicating devices (shown in Figure 6). Such a system will work quite well in the presence of a target which produces a signal above the system noise.

At this point, it is necessary to ask what the performance of this system is in the absence of a target. Since the loop is open (that is, no correspondence exists between the position of the lens and the signal out of the infrared detectors), the system is free to take up any position. For example, noises in the system might actuate the relay in such a way as to drive the positioning motor to one stop. This might happen rapidly or in random fashion. In order to prevent this, it is possible to disable the tracking motor when there is no infrared signal present, thus causing the system to remain at the last position occupied by the lens prior to loss of the signal.

This is undesirable for several reasons. First, it is difficult to know when the system has an infrared signal. Second, if the motor circuit is disabled, then undesirably large transients may be introduced when the loop is reestablished in the presence of an infrared signal. Such transients may tend to overload the system and would cause undesired oscillation or loss of target signal.

Therefore, we construct a second loop, as shown in Figure 7. This second loop consists of mechanically

coupling the physicial position of the primary lens to a gyroscope. The gyroscope output signal is summed with the detector output at the input to the amplifier. The amplifier drives a relay; the relay drives a motor, and the motor is coupled mechanically to the primary lens and to the wiper arm of the position-indicating potentiometer P. It is now evident that in the absence of an infrared signal, motion of the primary lens will cause the gyro to generate a signal.

is position-controlled in such a way as to make it look along the line-of-sight without respect to motions of the missile axis.

The addition of the second loop has another advantage. In the presence of an infrared signal, the rate at which the head tracks the target is now proportional with the magnitude of the target displacement from boresight. This fact tends to make the head track more smoothly and to produce better data. It

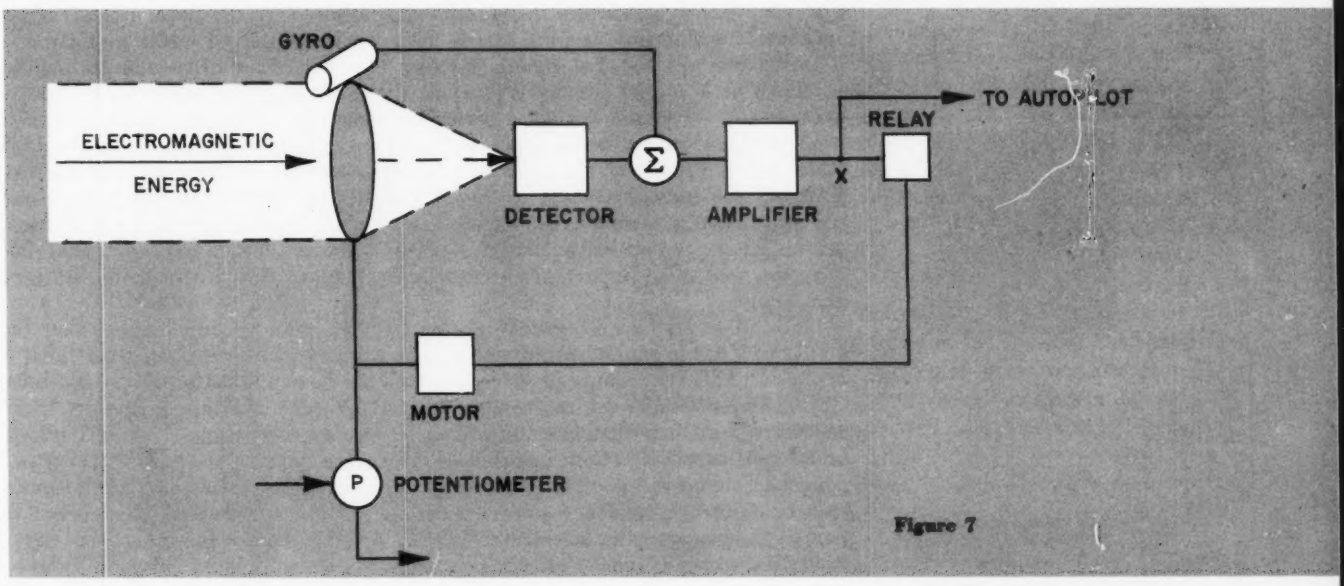

Figure 7

The signal will actuate the motor through the amplifier-relay blocks in such a direction as to reduce the lens velocity to zero. The addition of this second loop (which is a so-called velocity, rather than a position, loop) causes both the velocity and position of the primary lens to be zero in the absence of an infrared signal.

Notice that one other desirable result was obtained by mounting gyroscopes on the primary lens and by using the gyroscope signal to help control the lens position. It should be evident now that the position of the primary lens in inertial coordinates has been reduced to a constant. If the lens attached to the missile were to take up a rotation around one missile coordinate as the missile accelerated in a given direction, this would constitute motion of the lens in inertial coordinates. The gyroscope would sense such motion, however, and would generate a signal of sufficient magnitude to control the motor and cause the lens to rotate in the opposite direction. In effect, the missile is rotating and the lens is not. Thus, for motions of the missile in inertial space, the direction of the line-of-sight is unaffected and the primary lens

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We have established that, by means of the radiant energy from a target, we can detect that target; that, by making use of the direction of arrival of this energy, we can determine the direction of the target, and can sense the rate of rotation of the line-of-sight between the missile and the target. These two pieces of information are required by the missile autopilot for the missile to steer a collision course. Certain computations are performed on these signals prior to feeding them to the autopilot; these computations are based on the characteristics of the particular missile in use.

The ideas expressed in this explanation of the principles of infrared guidance of homing missiles are, of necessity, only basic. Far more complex extensions of the principles discussed must be used in the fabrication of an actual missile system.

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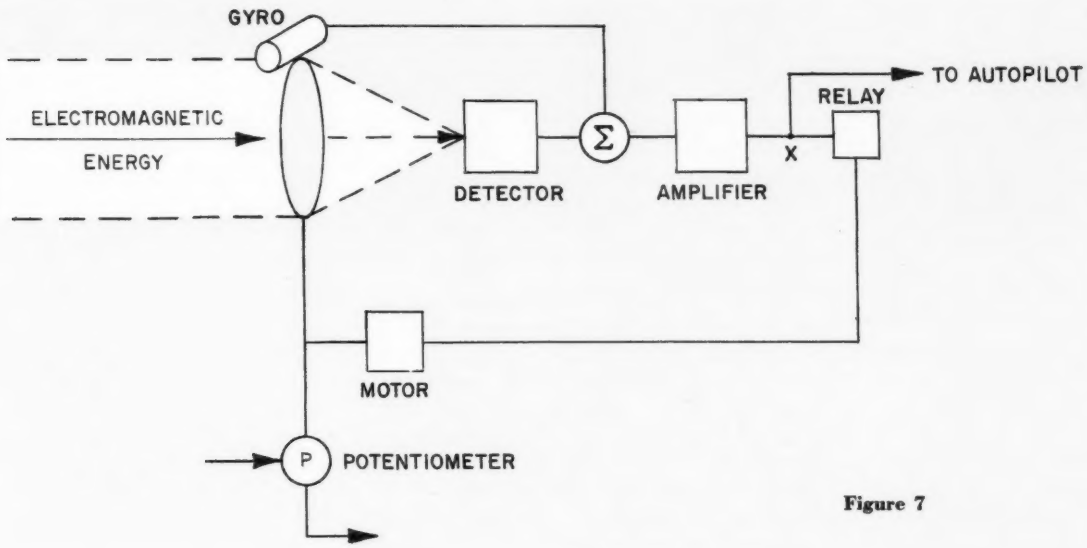

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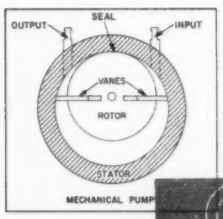
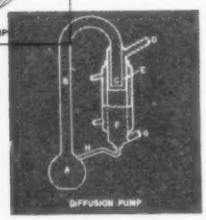
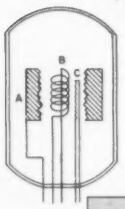
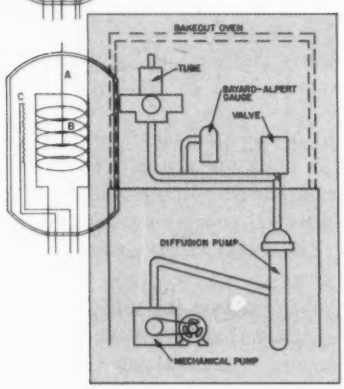
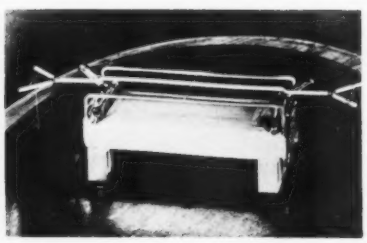










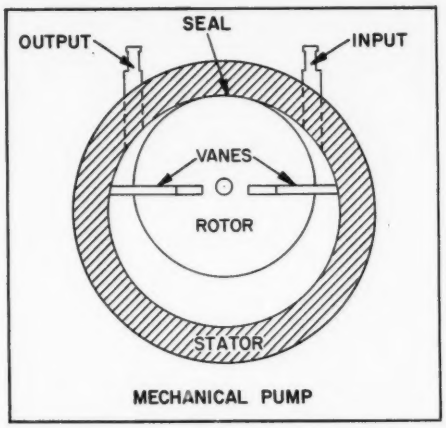
Great interest in vacuum technology was aroused by the development of the incandescent filament vacuum lamp. This interest received additional impetus with the development of electronic devices. The importance of vacuum technology is shown with a brief summary of some of the applications. There is the entire spectrum of electronic devices, ranging from the 100 KW transmitting tubes to the sub-miniature receiving types. In the field of nucleonics there are the high voltage devices such as the cyclotron, betatron and two-million volt x-ray tubes. Further, the industrial uses of vacuum distillation, vacuum dehydration and vacuum fusion of metals have increased to a startling extent. Vacuum techniques are no longer the exclusive province of the scientific laboratory, therefore, but have emerged as an important engineering technology that is increasing by leaps and bounds.

Reduced to its bare essentials, the production of a vacuum depends on the ability of a gas to expand rapidly and to fill completely any container in which it is placed. This very handy property of gases can be explained in this way. Atoms and molecules tend to diffuse from regions of high concentration to those of lower concentration, until there is a uniform concentration throughout the closed system under consideration. (Concentration is simply the number of atoms or molecules per unit volume and is directly proportional to pressure.) In a mixture of gases each exhibits this tendency toward equalization independent of the others. If part of the gas atoms in a system are trapped and removed, the others will move in to fill the vacant space until the concentration is again equal (although lower) throughout the system. This is a reasonably elementary concept but it is the one on which vacuum technology rests. The trick involved is to trap the molecules or atoms and remove them efficiently from the system. There is also the subsidiary trick of finding out how many have been removed by measuring the pressure of the system.

Given the problem of trapping the gases from a closed container, a mechanical engineer would come up with some variation on a piston moving in a cylinder connected to the container with valves that open and close at the right time — or in simple language, a pump. This is a valid way to proceed, and varied indeed are the possible designs of this mechanical pump.

One of the more popular pumps, a rotary type, is shown in Figure 1. A rotor is mounted eccentrically with reference to a stator and two metal vanes, spring loaded to press against the stator walls, move in and out of their slots as the rotor revolves. A crescent-shaped air space is thereby swept out twice per revolution. The inlet and outlet ports are sealed from each other by a thin film of oil. This pump under ideal conditions will attain a pressure of 5×10^{-4} mm Hg. (For reference, atmospheric pressure is about 760 mm Hg.)

A physicist given the same problem of trapping and removing the gas would probably think of something more esoteric — for example, the diffusion pump. This pump works on the ingenious principle of trapping and removing the gas molecules in a high speed stream of vapor molecules. The vapor molecules must have the property that they can be condensed out of the gas stream so that they will not diffuse into the high vacuum region. For this reason, high boiling oils or mercury are used as the entrapping vapors which are produced by heating. To insure that there is no diffusion of the condensible vapors back into the evacuated space, a very low temperature region (cold trap) is inserted between the evacuated space and the diffusion pump. Figure 2 shows one among the



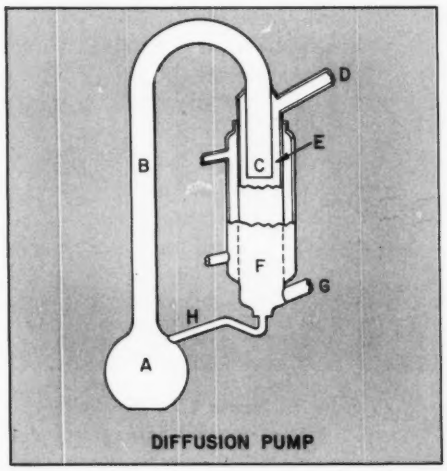


Figure 2

literally hundreds of diffusion pump designs in use. Mercury or oil from boiler A is carried through thermally insulated tube B to nozzle C. The container to be evacuated is connected to D. The gas from this vessel diffuses into annular space E, where it comes into contact with oil or mercury vapor from nozzle C and is forced downward into the space F, from which it escapes into outlet G. Diffusion pumps will operate only against low pressures, so a mechanical pump is connected to G to provide the "rough" vacuum. Mercury or oil, which is condensed in the region below E, is returned to the boiler by connection H. A pump such as this will reach a limiting vacuum of at least 10^{-7} mm Hg. It can be fabricated either from metal or glass.

A chemist given the problem of ridding himself of the gases in the to-be-evacuated container would proceed to trap the gas molecules by reacting them with something which would tie them up in solid non-volatile compounds. On this principle has been built the technique of "gettering," so important in the production of radio tubes. Certain active metals such as barium and titanium will react with the common gases in air forming solid non-volatile oxides, nitrides and carbides, which effectively remove the gases from the system. Of course, the noble gases such as helium, argon and neon are impervious to this treatment and remain behind to keep the pressure high. A variation on this theme is to use a cold trap containing liquid helium which freezes all the other gases out of the system. By this means, a very good vacuum indeed can be obtained.

All of the above methods alone or in combination are in use for the production of vacua — which one or which combination depends on how high a vacuum is required and how fast it must be achieved. All vacuum pumps are specified by two main criteria: speed and limiting vacuum. Pumping speed is just what it indicates, the rate at which the gas molecules are extracted from the system. It varies directly with pressure, and this in turn defines the ultimate attainable vacuum, the pressure at which pumping speed becomes zero. When a pump is used in an actual system, the leak rate of the system and the speed of the pump become equal at some particular pressure. Therefore, the best vacuum obtainable in a given system depends on both the pumping speed and the system's own "tightness."

Vacuum technology can be divided into three categories — low vacuum (covering pressures from atmospheric to 10^{-4}), high vacuum (from 10^{-4} to 10^{-7}) and ultra-high vacuum (from 10^{-7} down). Low vacua are generally produced by mechanical pumps alone. High and ultra-high vacua require mechanical pumps plus diffusion pumps and/or active metal gettering, not to mention the patience of Job and the Luck of the Irish.

The measurement of pressure can be accomplished in any of a number of ways. The simplest is to compare the pressure to atmospheric by measuring the height of a column of mercury that the atmosphere can sustain against the vacuum. This method, however, is insensitive at low pressures. One can instead abstract a small known volume of the gases in the vacuum, measure that volume at a higher pressure and using the ideal gas law, calculate what the original pressure must have been. The viscosity of the gases left in the system is also measurable and directly proportional to the pressure. Or one can make use of the decrease in thermal conductivity of gases with lowering pressure. All of these methods, and others, are currently in use; all have a specific range of pressures over which they operate most efficiently.

From 10^{-3} mm Hg on down, the most popular means of measuring pressure (and indeed the only means in the extremely low pressure regions) is the ionization gauge. This works on the principle of ioniz-

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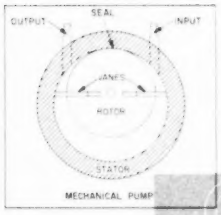

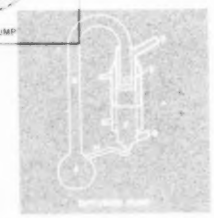

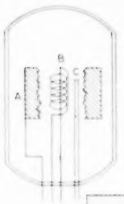

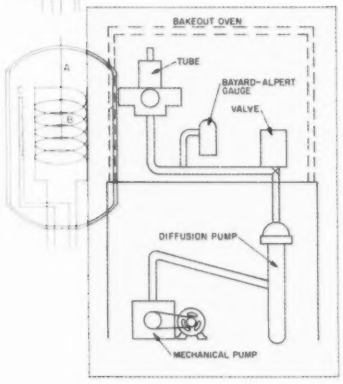

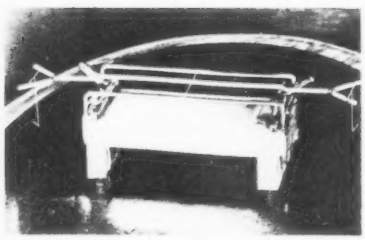

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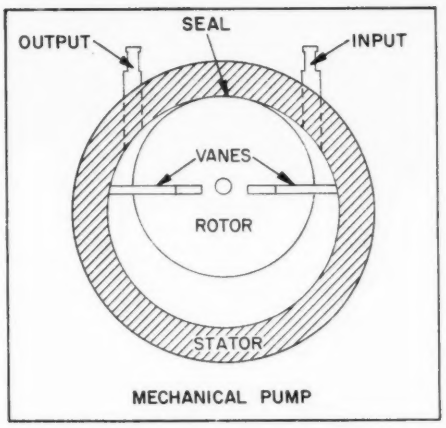
A physicist given the same problem of trapping and removing the gas would probably think of something more esoteric — for example, the diffusion pump. This pump works on the ingenious principle of trapping and removing the gas molecules in a high speed stream of vapor molecules. The vapor molecules must have the property that they can be condensed out of the gas stream so that they will not diffuse into the high vacuum region. For this reason, high boiling oils or mercury are used as the entrapping vapors which are produced by heating. To insure that there is no diffusion of the condensible vapors back into the evacuated space, a very low temperature region (cold trap) is inserted between the evacuated space and the diffusion pump. Figure 2 shows one among the



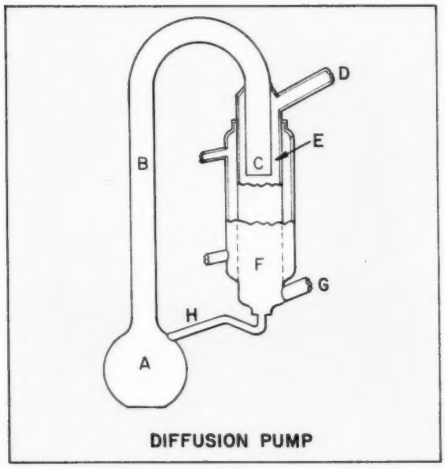


Figure 2

literally hundreds of diffusion pump designs in use. Mercury or oil from boiler A is carried through thermally insulated tube B to nozzle C. The container to be evacuated is connected to D. The gas from this vessel diffuses into annular space E, where it comes into contact with oil or mercury vapor from nozzle C and is forced downward into the space F, from which it escapes into outlet G. Diffusion pumps will operate only against low pressures, so a mechanical pump is connected to G to provide the "rough" vacuum. Mercury or oil, which is condensed in the region below E, is returned to the boiler by connection H. A pump such as this will reach a limiting vacuum of at least 10^{-7} mm Hg. It can be fabricated either from metal or glass.

A chemist given the problem of ridding himself of the gases in the to-be-evacuated container would proceed to trap the gas molecules by reacting them with something which would tie them up in solid non-volatile compounds. On this principle has been built the technique of "gettering," so important in the production of radio tubes. Certain active metals such as barium and titanium will react with the common gases in air forming solid non-volatile oxides, nitrides and carbides, which effectively remove the gases from the system. Of course, the noble gases such as helium, argon and neon are impervious to this treatment and remain behind to keep the pressure high. A variation on this theme is to use a cold trap containing liquid helium which freezes all the other gases out of the system. By this means, a very good vacuum indeed can be obtained.

All of the above methods alone or in combination are in use for the production of vacua — which one or which combination depends on how high a vacuum is required and how fast it must be achieved. All vacuum pumps are specified by two main criteria: speed and limiting vacuum. Pumping speed is just what it indicates, the rate at which the gas molecules are extracted from the system. It varies directly with pressure, and this in turn defines the ultimate attainable vacuum, the pressure at which pumping speed becomes zero. When a pump is used in an actual system, the leak rate of the system and the speed of the pump become equal at some particular pressure. Therefore, the best vacuum obtainable in a given system depends on both the pumping speed and the system's own "tightness."

Vacuum technology can be divided into three categories — low vacuum (covering pressures from atmospheric to 10^{-4}), high vacuum (from 10^{-4} to 10^{-7}) and ultra-high vacuum (from 10^{-7} down). Low vacua are generally produced by mechanical pumps alone. High and ultra-high vacua require mechanical pumps plus diffusion pumps and/or active metal gettering, not to mention the patience of Job and the Luck of the Irish.

The measurement of pressure can be accomplished in any of a number of ways. The simplest is to compare the pressure to atmospheric by measuring the height of a column of mercury that the atmosphere can sustain against the vacuum. This method, however, is insensitive at low pressures. One can instead abstract a small known volume of the gases in the vacuum, measure that volume at a higher pressure and using the ideal gas law, calculate what the original pressure must have been. The viscosity of the gases left in the system is also measurable and directly proportional to the pressure. Or one can make use of the decrease in thermal conductivity of gases with lowering pressure. All of these methods, and others, are currently in use; all have a specific range of pressures over which they operate most efficiently.

From 10^{-3} mm Hg on down, the most popular means of measuring pressure (and indeed the only means in the extremely low pressure regions) is the ionization gauge. This works on the principle of ioniz-

ing the gases remaining in the system by collision with electrons and then measuring the ion current so produced. Almost any three-element radio tube will work as an ionization gauge, if the elements are biased properly. The electrons from a heated cathode are accelerated by a field between the cathode and anode to potential energies sufficient to ionize the gases. The third element is given a negative potential and serves as an ion collector. Over wide ranges, the pressure is a linear function of the ion current, all other parameters being held constant. There is a large technology concerning design for most efficient operation and for calibrating to read pressure in known units.

There has arisen in recent years a technology of ultra-high vacuum. The break-through which allowed the development of this technology was the discovery of the means of measuring pressures in the range of 10^{-7} to 10^{-11} mm Hg. This discovery in turn had depended on a careful investigation of the limitations of ionization gauges. Over the years, many workers found that they could never get pressure readings much below 10^{-7} mm Hg, although, in many cases, they were morally sure that they should have lower pressures than that in their system. Gradually, the idea developed that ionization gauges must be limited in some way in operation at very low pressures. This limitation was found. There is a residual current to the ion collector and this current is completely independent of pressure. It is caused by the soft x-rays created when electrons from the filament strike the anode. These x-rays in turn release from the ion collector photo-electrons which are accelerated to the anode and give an apparent ion current. The solution to this problem was to make the geometric area of the ion collector very small so that few x-rays would be intercepted. The differences in design for a conventional ionization gauge and for one designed to minimize the residual ion current are shown in Figure 3. The simple change in design immediately pushed the possible range of pressure measurement down four orders of magnitude to 10^{-11} mm Hg and opened a whole new area of ultra-high vacuum technology.

Another important development in high vacuum technology was the realization that the ionization gauge itself is an efficient vacuum pump at low pressures. The positive ions which are formed by electron bombardment are driven into negatively charged surfaces of the gauge where they are neutralized and trapped within the solid surface. In particular, it has been shown that the glass walls of the ionization gauge assume a potential very close to that of the hot cathode; therefore, ions can be trapped at the glass envelope of the gauge.

The final necessity for obtaining ultra-high vacua is a thorough baking-out at elevated temperatures of all surfaces exposed to the very low pressures. This

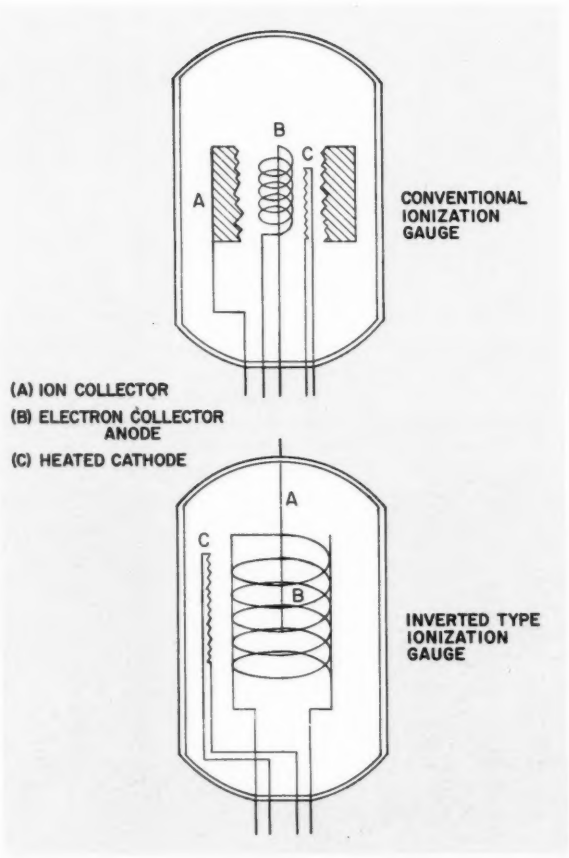


Figure 3

need arises from the fact that all materials exposed to air absorb a certain quantity of these gases in and on their surfaces. When the materials are exposed to high vacuum, these gases are released, but in almost all cases the release is very slow. This slow release constitutes a source of gas within the system and very efficiently prevents the attainment of high vacuum. Heating accelerates enormously the release of these absorbed gases, but even so, it is necessary to bake a system for as long as 48 hours at 400°C before obtaining the ultimate in ultra-high vacua.

The various requirements and instrumentations for obtaining ultra-high vacua have been worked out thoroughly. A novice in the field can now have a system capable of 10^{-10} mm Hg in the time necessary to order the parts and have a glass blower stick them together.

The most time-consuming and exasperating aspect of high or ultra-high vacuum technology is the small leak that may occur in the system. The importance of this problem can be realized by considering that a multi-million dollar electron accelerator which would fill a good-sized ballroom can be put out of commission

by a few holes much smaller in diameter than a pin. Much ingenuity and effort has been expended in developing instruments and techniques which will aid in the rapid detection and location of leaks. Not recommended is the technique offered the author by a crusty university professor who, after listening to the sad story of a leaky system, said, "Pack it full of sugar and watch where the ants crawl in." Actually, any vacuum system will have leaks and it depends on the pressure range of operation and the pumping speed whether they are important or not. A small leak which is not noticeable at 10^{-4} mm Hg will look terribly large at 10^{-8} mm Hg. This creates the first axiom in leak detection: pump the system to the lowest possible pressure.

Probably the greatest boon to rapid leak detection and location is the mass spectrometer. For leaks, an instrument set to respond only to helium is used. Helium gas is chosen because it has a low atomic weight. This is desirable since gas will diffuse through a small opening at a rate which is inversely proportional to the square root of its molecular weight. Furthermore, helium is an extremely rare gas and the chances of spurious effects due to local contamination are small. The mass spectrometer is connected to the vacuum system; a small jet of helium from a tank is played over suspect areas of the system, while one eye watches the ion current indicator in the mass spectrometer. When the needle jumps, the helium jet has passed over a small leak. In this way, leaks which at one time required days and even weeks of hunting can now be found very quickly.

All systems are limited by the ultimate leak rate, which is the rate at which gases from the atmosphere diffuse through the walls of the vacuum vessel. It has been found that glass systems seem to have a limiting leak rate of about 3×10^{-11} mm Hg-liters per minute. This has been attributed to helium from the atmosphere diffusing through the glass walls of the system. This doesn't present much of a problem for vacua of 10^{-10} mm Hg, but at 10^{-13} mm Hg, it would be all-important. It is interesting to speculate concerning this leak rate. If a glass vessel of 1 liter volume had been evacuated at about the time of the last dinosaur walking the earth in the Mesozoic era, and placed in an ambient of helium at 1 atmosphere, the internal pressure would now be approaching atmospheric. It is interesting to note that a leak rate of this magnitude can be measured in the laboratory.

Ultra-high vacuum techniques are still largely confined to the scientific laboratory. The ability to prepare and keep a surface really clean, free from any absorbed and/or adsorbed gas atoms or molecules at 10^{-10} mm Hg, is allowing rapid expansion of knowledge on surface chemistry and physics. But also, more and more, ultra-high vacuum technology is taking its place with high vacuum technology as an important industrial tool.

An Industrial Application of Vacuum Technology . . .

The Detection of Microleaks

I. P. Fish
Microwave and Power Tube Division

Leaks have plagued the vacuum tube industry since its beginning. Particularly annoying are those leaks too small to be found by conventional means but large enough to cause loss of vacuum during the otherwise normal life of the tube. The ability to produce and measure pressures in the ultra-high vacuum range (lower than 10^{-7} mm Hg) has made it possible to locate these small leaks, termed microleaks.

Leak rates are measured in terms of pressure-volume per unit time, frequently expressed in micron-liters per second.

$$Q = \frac{(\Delta P)(V)}{(t)}$$

where Q equals leak rate, ΔP the change in pressure, t the time required for this change, and V the volume of this system. For example, a leak rate of 5×10^{-6} micron-liters per second would cause the pressure in a tube of 1 liter volume to increase from 1×10^{-6} to 2×10^{-6} mm Hg in 200 seconds. If this vacuum tube, sealed at a pressure of 1×10^{-6} mm Hg, would fail to operate or become "soft" at a pressure of 1 micron (10^{-3} mm Hg), its useful life would be 2×10^{5} seconds or about 55 days from the time of exhaust.

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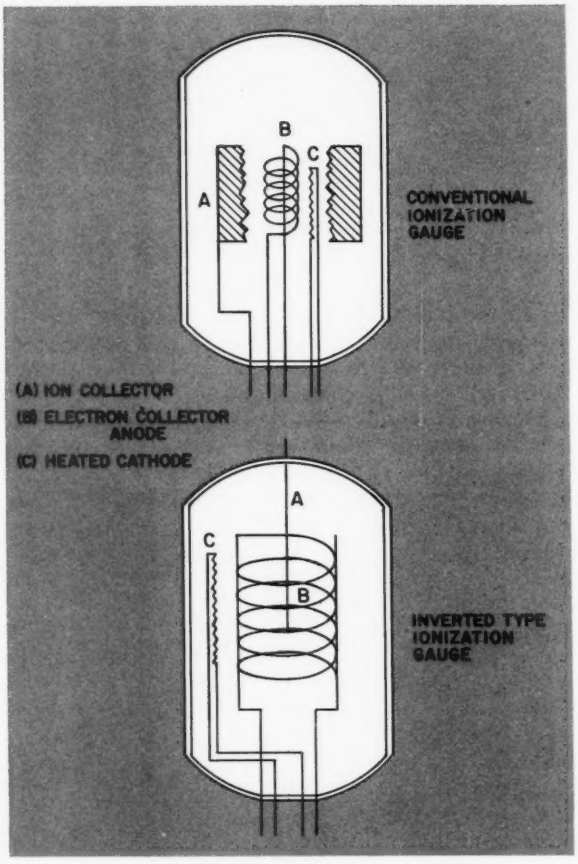

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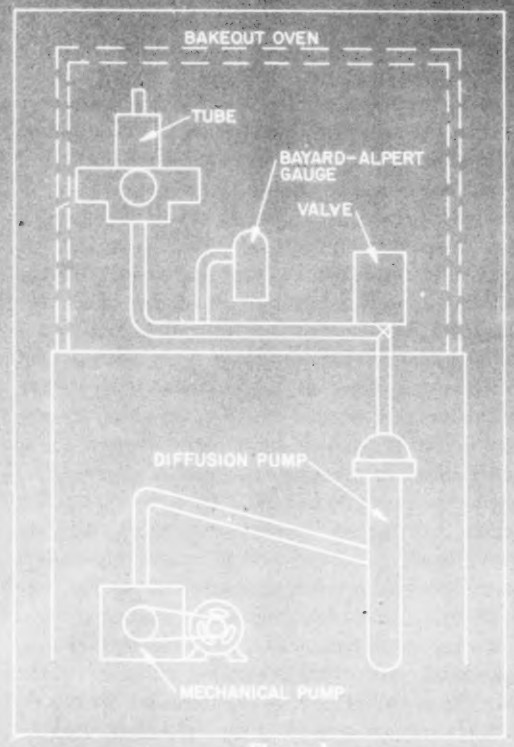

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1×10^{-8} mm Hg can be achieved for this system, the same leak rate will result in a pressure increase to 1×10^{-7} in less than 20 seconds, a large change easily noted. Use of a sensitive pressure gauge such as the Bayard-Alpert inverted structure type ionization gauge, permits the ready measurement of pressure in this range. This gauge is also capable of pumping a well degassed system from the high vacuum to ultra-high vacuum range, as long as there are no large leaks. The ultimate pressure will depend on outgassing and leakage.

The leak rates discussed have referred to air as the gas surrounding the tube. If this enveloping gas is replaced by a lighter one, the leak rate will be increased as the inverse square root of the molecular weights. Replacing air with helium results in a leak rate increased by a factor of 2.7 or, in the example given here, to 1.35×10^{-5} micron-liters per second. By combining helium envelopment with the Bayard-Alpert gauge, the sensitivity is significantly increased.

Reducing the volume of a vacuum system provides still greater sensitivity in microleak detection, since a lower ultimate pressure can be achieved and a given leak rate will cause a more rapid change in pressure. In the microleak detection procedure which has been in use in the Microwave Power Tube Research and Development Laboratory for several years, a high vacuum valve is inserted between the Bayard-Alpert gauge and the pumps. The diagram (Figure 1) shows the arrangement of the entire exhaust system equipped to detect microleaks. Any conventional vacuum tube exhaust processing station can be adapted in this manner by adding the gauge and valve, as all of the other ingredients for a high vacuum system are already present.

The exhaust process is carried out in the usual manner, baking the tube at as high a temperature as possible until its walls and internal parts are thoroughly outgassed. After degassing the gauge itself, the pressure of the system can be measured and, assuming no large leaks, should be in the range of the ultimate capability of the high vacuum parts of the system (1×10^{-7} to 1×10^{-6} mm Hg).

Closing the valve isolates the remainder of the system, leaving only those parts which should be capable of attaining pressures in the ultra-high vacuum range. The ionization gauge then pumps the system to an equilibrium pressure limited by gas evolution and leaks. Enveloping the tube in helium by enclosing it in a gas-filled plastic bag will cause an increase in pressure if there are any leaks large enough to be detected by this method, due to the greater leak rate of helium. Leaks can be pinpointed by probing suspected areas of the tube envelope with a small jet of helium. By starting at the top of the tube and working slowly downward, a leak can be accurately located. Once located, hopefully the leak can be repaired.

In experimental tubes many small leaks can be sealed effectively without removing the tube from the vacuum system, enabling the development engineer to obtain the test data desired. One sealant used successfully is a catalyzed acrylic monomer known as MPL Monomer or Permafil. The catalyzed monomer is kept aerated to prevent polymerization until it is used to seal the leak. The sealant is brushed onto the leak area and becomes hard and infusible as air is excluded and polymerization occurs. This material will withstand temperatures of up to 200°C, and overheating seems to be the only way of removing it after it has hardened.

In microleak detection, ultra-high vacuum techniques have assumed an important industrial role as a useful engineering and production tool. During the past several years, thousands of tubes have been checked in the Microwave Power Tube Research and Development Laboratory. Many leaks have been found that would otherwise have gone undetected. The vacuum tube engineer has been given useful information to apply to brazed or welded joint design and to the techniques of ceramic or glass-to-metal seals. The detection and elimination of microleaks is an important step forward in meeting the increasing demands for long life and reliability of vacuum tubes.

A Research Application of Vacuum Technology . . .

Using a Microbalance to Study Semiconductors

S. P. Wolsky
Research Division

In order to design and make reliable semiconductor devices, it is necessary to possess information concerning the basic properties of the semiconductor materials. These properties may be separated into the general categories of bulk and surface. Although the bulk and surface properties may usually be studied independently, the observed behavior of such a device is due to the net effect of both. In fact, as understanding and the ability to control bulk properties progressed, it became very apparent that the surface effects predominated to the extent that they essentially determined the device performance. With this recognition there came an increased effort devoted to the study of the surface properties of semiconductors, specifically germanium and silicon.

The surface investigations have been devoted to a study of the electrical properties (as determined, for example, from conductivity measurements), and a determination of the chemical nature of the surface (from kinetic and adsorption experiments). The electrical behavior has been studied extensively so that the nature, density, and position of the energy states at the surface of germanium and silicon are fairly well known. Unfortunately, understanding of the chemical nature of these surfaces has not progressed as rapidly, with the result that it is still not possible to prescribe the treatment necessary for the attainment of the optimum surface for device operation.

In considering the techniques available for obtaining adsorption and kinetic information, it is necessary to determine not only the most sensitive method but also that which could be readily adapted to other gas-solid studies. In this respect one of the most powerful experimental tools for the investigation of gas-solid reactions is the vacuum microbalance. The apparatus consists essentially of a very sensitive quartz microbalance which operates directly in vacuum and provides a continuous record of the experimental process. With this gravimetric technique, it is possible to work with samples of approximately 10 cm^2 total surface area. The necessity of working with the comparatively large area powdered or crushed samples demanded by more conventional volumetric adsorption techniques is eliminated. Differences in behavior due to crystal orientation can be detected using single crystal slices. Such studies have been very successfully performed using copper and zinc. The vacuum microbalance apparatus also satisfies the requirement of versatility. Although originally set up chiefly for the determination of the oxidation kinetics of germanium and silicon, the same apparatus has been used in this laboratory to determine the solubility of gases in solids and the effect of positive ion bombardment on solids.

Since the basic microbalance technique is quite interesting, it will be described in detail here. The very sensitive quartz microbalance has been set up in an ultra-high vacuum system. Figure 1 presents a schematic representation of the balance. The precision-made quartz beam (0.075 in. diameter) is supported on a 0.001 in. tungsten wire. The end supports are 0.0005 in. tungsten wire. The wires are joined to the beam and quartz frame with fused silver chloride. Iron cores sealed in small quartz sections allow external manipulation of the balance arrests by means of a small magnet. Static charge effects are eliminated

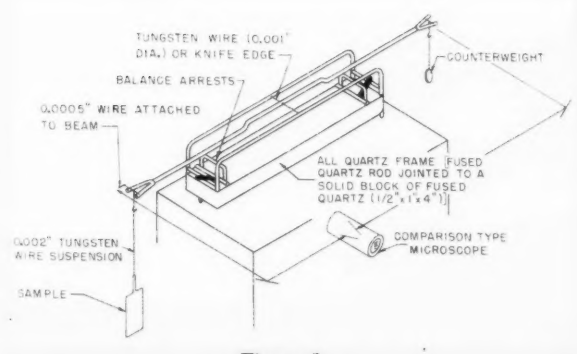

TUNGSTEN WIRE (0.001" DIA.) OR KNIFE EDGE
COUNTERWEIGHT
BALANCE ARRESTS
0.0005" WIRE ATTACHED TO BEAM
ALL QUARTZ FRAME (FUSED QUARTZ ROD JOINTED TO A SOLID BLOCK OF FUSED QUARTZ (1/2"×1"×4"))
COMPARISON TYPE MICROSCOPE
0.002" TUNGSTEN WIRE SUSPENSION
SAMPLE

Figure 1

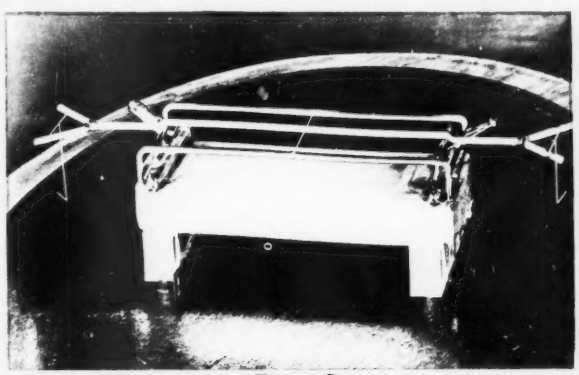
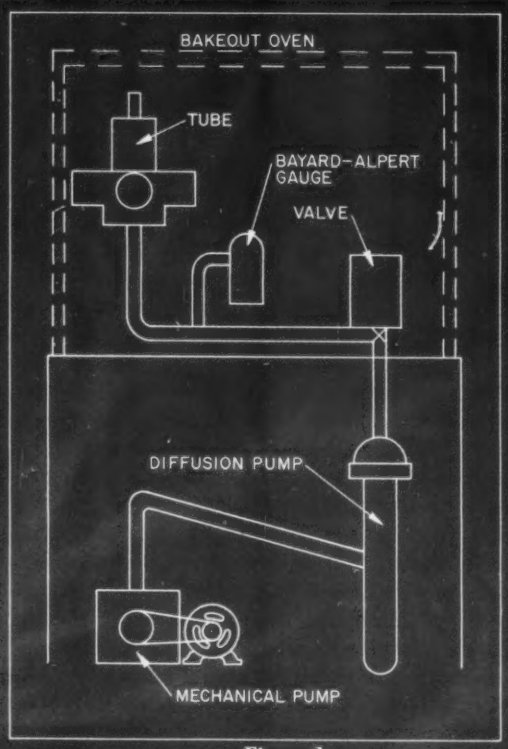


Figure 2



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Closing the valve isolates the remainder of the system, leaving only those parts which should be capable of attaining pressures in the ultra-high vacuum range. The ionization gauge then pumps the system to an equilibrium pressure limited by gas evolution and leaks. Enveloping the tube in helium by enclosing it in a gas-filled plastic bag will cause an increase in pressure if there are any leaks large enough to be detected by this method, due to the greater leak rate of helium. Leaks can be pinpointed by probing suspected areas of the tube envelope with a small jet of helium. By starting at the top of the tube and working slowly downward, a leak can be accurately located. Once located, hopefully the leak can be repaired.

In experimental tubes many small leaks can be sealed effectively without removing the tube from the vacuum system, enabling the development engineer to obtain the test data desired. One sealant used successfully is a catalyzed acrylic monomer known as MPL Monomer or Permafil. The catalyzed monomer is kept aerated to prevent polymerization until it is used to seal the leak. The sealant is brushed onto the leak area and becomes hard and infusible as air is excluded and polymerization occurs. This material will withstand temperatures of up to 200°C, and overheating seems to be the only way of removing it after it has hardened.

In microleak detection, ultra-high vacuum techniques have assumed an important industrial role as a useful engineering and production tool. During the past several years, thousands of tubes have been checked in the Microwave Power Tube Research and Development Laboratory. Many leaks have been found that would otherwise have gone undetected. The vacuum tube engineer has been given useful information to apply to brazed or welded joint design and to the techniques of ceramic or glass-to-metal seals. The detection and elimination of microleaks is an important step forward in meeting the increasing demands for long life and reliability of vacuum tubes.

A Research Application of Vacuum Technology . . .

Using a Microbalance to Study Semiconductors

S. P. Wolsky
Research Division

In order to design and make reliable semiconductor devices, it is necessary to possess information concerning the basic properties of the semiconductor materials. These properties may be separated into the general categories of bulk and surface. Although the bulk and surface properties may usually be studied independently, the observed behavior of such a device is due to the net effect of both. In fact, as understanding and the ability to control bulk properties progressed, it became very apparent that the surface effects predominated to the extent that they essentially determined the device performance. With this recognition there came an increased effort devoted to the study of the surface properties of semiconductors, specifically germanium and silicon.

The surface investigations have been devoted to a study of the electrical properties (as determined, for example, from conductivity measurements), and a determination of the chemical nature of the surface (from kinetic and adsorption experiments). The electrical behavior has been studied extensively so that the nature, density, and position of the energy states at the surface of germanium and silicon are fairly well known. Unfortunately, understanding of the chemical nature of these surfaces has not progressed as rapidly, with the result that it is still not possible to prescribe the treatment necessary for the attainment of the optimum surface for device operation.

In considering the techniques available for obtaining adsorption and kinetic information, it is necessary to determine not only the most sensitive method but also that which could be readily adapted to other gas-solid studies. In this respect one of the most powerful experimental tools for the investigation of gas-solid reactions is the vacuum microbalance. The apparatus consists essentially of a very sensitive quartz microbalance which operates directly in vacuum and provides a continuous record of the experimental process. With this gravimetric technique, it is possible to work with samples of approximately 10 cm^2 total surface area. The necessity of working with the comparatively large area powdered or crushed samples demanded by more conventional volumetric adsorption techniques is eliminated. Differences in behavior due to crystal orientation can be detected using single crystal slices. Such studies have been very successfully performed using copper and zinc. The vacuum microbalance apparatus also satisfies the requirement of versatility. Although originally set up chiefly for the determination of the oxidation kinetics of germanium and silicon, the same apparatus has been used in this laboratory to determine the solubility of gases in solids and the effect of positive ion bombardment on solids.

Since the basic microbalance technique is quite interesting, it will be described in detail here. The very sensitive quartz microbalance has been set up in an ultra-high vacuum system. Figure 1 presents a schematic representation of the balance. The precision-made quartz beam (0.075 in. diameter) is supported on a 0.001 in. tungsten wire. The end supports are 0.0005 in. tungsten wire. The wires are joined to the beam and quartz frame with fused silver chloride. Iron cores sealed in small quartz sections allow external manipulation of the balance arrests by means of a small magnet. Static charge effects are eliminated

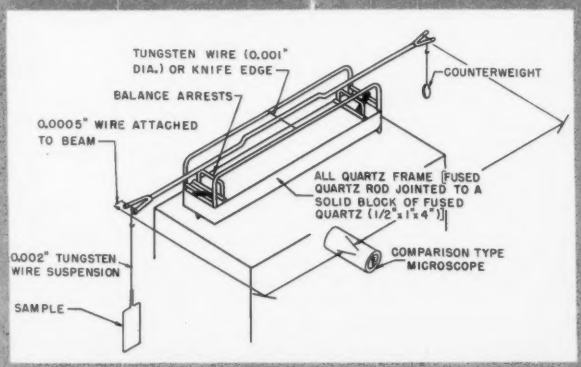
TUNGSTEN WIRE (0.001" DIA.) OR KNIFE EDGE
COUNTERWEIGHT
BALANCE ARRESTS
0.0005" WIRE ATTACHED TO BEAM
ALL QUARTZ FRAME FUSED QUARTZ ROD JOINTED TO A SOLID BLOCK OF FUSED QUARTZ (1/2"x1"x4")
0.002" TUNGSTEN WIRE SUSPENSION
COMPARISON TYPE MICROSCOPE
SAMPLE

Figure 1

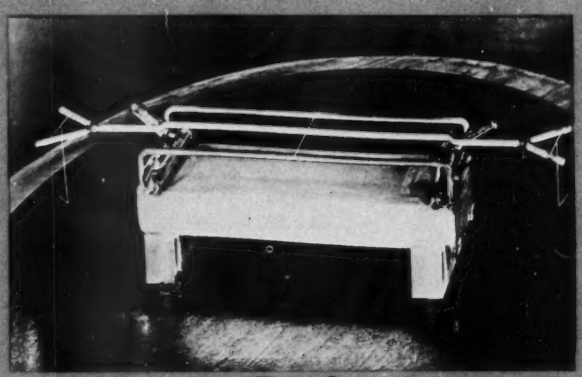

Figure 2

by a ground connection to a conductive coating of platinum or gold evaporated onto the balance. The balance tubes are also grounded through an aquadag film. Weight changes are followed from observation of the deflection of the beam ends onto the fixed scale in the eyepiece of a specially designed comparison-type microscope. The balance is calibrated by measuring the deflection from an observed zero point caused by known weight differences. Due to the careful design of the balance and associated system, buoyancy effects are less than the sensitivity at all pressures used. The capacity of the balance is one gram. Weight differences of 0.1 microgram (less than three-billionths of an ounce) can be reproducibly detected. Such sensitivity is necessary for a study of the infinitesimal quantities of surface impurities which markedly affect the properties of semiconductor devices. Figure 2 is a photograph of the quartz balance.

The vacuum microbalance system is represented schematically in Figure 3. The balance is enclosed in a Pyrex case which is connected through a double liquid-nitrogen trap with two mercury diffusion pumps working in series. The balance case and hangdown tubes are thermostatted. After a bakeout of 12 to 36 hours, a vacuum of 5×10^{-10} mm is usually obtained, as read on a Westinghouse WL5966 Bayard-Alpert ionization gauge. This gauge also serves as an ion-pump in the very low pressure region. Only metal valves capable of withstanding bakeout are used. No stopcocks or greased joints can be used if very low pressures are desired. The bakeout temperature is limited by the fused silver chloride, which exhibits plastic flow at 300°C. Molybdenum and titanium getters are used to reduce further the partial pressure of oxygen. The concentration of oxygen, therefore, is usually less than one ten-billionth of the total atmosphere in the system.

The sample is placed 22 inches below the balance beam by means of a 0.002 in. tungsten wire suspended from the beam-end cross wire. The specimen faces are parallel to the enclosing hangdown tube sides. The sample is heated with a small external heater which slides up around the hangdown tube. The quartz tubing in the sample region allows the use of temperatures up to approximately 1200°C. The lowest temperature at which measurements were made was —195°C (the boiling point of liquid nitrogen). This type of balance, however, has been used successfully even at liquid helium temperatures.

The balance is connected to a gas handling system through a metal valve and a series of break-off tips. In this region, pumped by its own vacuum system, manometers, ion gauges, and calibrated volumes are available for the preparation of gas samples of known pressure. Although stopcocks are used here, the system is thoroughly outgassed prior to an experiment and the gases passed through two liquid nitrogen traps (and a freshly flashed molybdenum getter, if desired) prior to admission to the sample area. Mass spectroscopic grade gases were used in all experiments. Figures 4, 5, and 6 are photographs of the vacuum microbalance and gas handling system and associated apparatus.

Single crystal oriented samples are used in all ex-

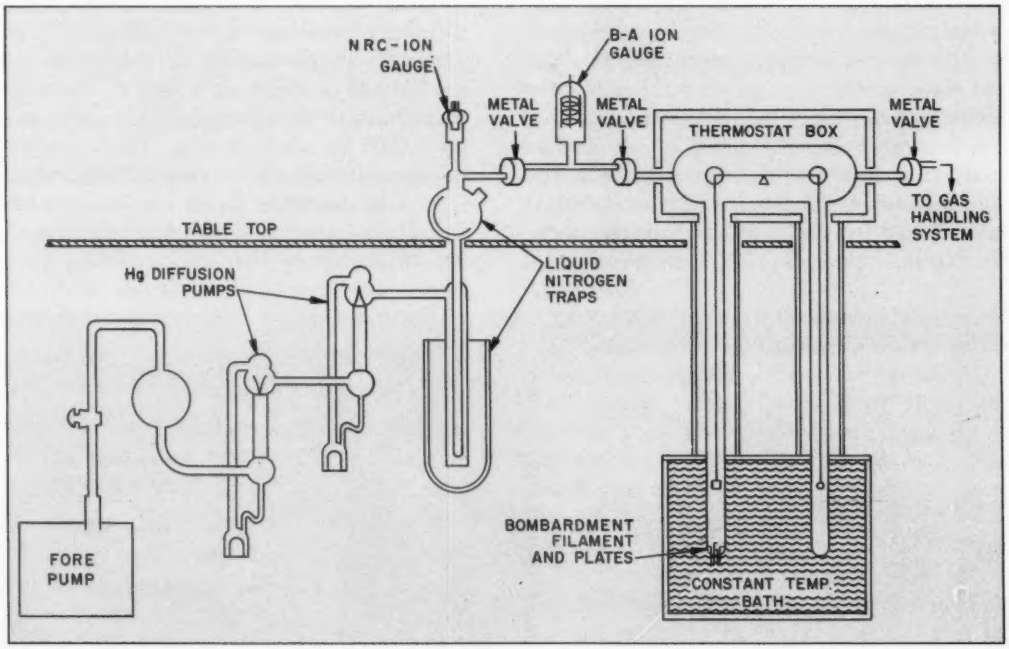

Figure 3

periments. The germanium and silicon samples are chemically etched with CP-4 to remove at least 0.005 in. from each face. The final sample plates are 0.002 to 0.004 in. thick and weigh approximately 0.3 gram. Geometric sample areas are 10-15 cm^2. The actual surface area as determined by low temperature adsorption (−195°C) of krypton or nitrogen is approximately 1.5 to 2 times greater than the geometric area. This is 10 to 100 times the area of a spherical counterbalance made of the same material as the sample plate and matched to within 10-100 μgrams of the weight of the plate. The counterbalance is held in a small platinum wire basket and suspended from the balance by means of a 0.002 in. tungsten wire.

The construction and handling of the balance requires a steady hand and considerable patience. The 0.0005 in. and 0.001 in. tungsten wires are sealed under tension to the balance by means of a small microtorch. Placing the sample on the balance requires extreme care, since the slightest strain on the very fine cross wires may alter the sensitivity of the balance or even cause the wire to break. Breaking of any one wire requires removal of the balance from the system for repair. Since no stopcocks or ground joints are used, considerable glass blowing skill is required in assembling the system. For example, in sealing the sample into the system, the glass-to-glass seal of the hangdown tubes is made with the sample in position suspended from the balance by the fine tungsten wire.

Since, in adsorption studies, the observed weight change is obviously dependent upon the surface area of the sample, increased sensitivity may be gained by use of powder samples. However, with powdered or crushed surfaces, an uncertainty concerning the orientation of the crystal faces is introduced. Active sites due to an increased number of corners, edges, and damaged surfaces may also have a significant effect upon the experimental process.

Provisions were made for positive ion and electron bombardment of the sample. A tungsten filament and two molybdenum plates are mounted on a standard four-pin tube base sealed into the bottom of the sample hangdown tube. A metallic shield was placed above the filament to prevent evaporated tungsten from depositing on the sample. All metal parts were thoroughly outgassed prior to use. Mass spectroscopic argon was further purified as described above prior to being admitted to the microbalance system. The pressure prior to admitting the inert gas was usually 10^{-9} mm or less. All bombardments were at an argon pressure of 10^{-3} to 10^{-4} mm.

With the grid plates +275 volts, an ionizing electron current of 10-50 ma was drawn by varying the emission of the filament. The ions formed were attracted to the sample, on which potentials of up to

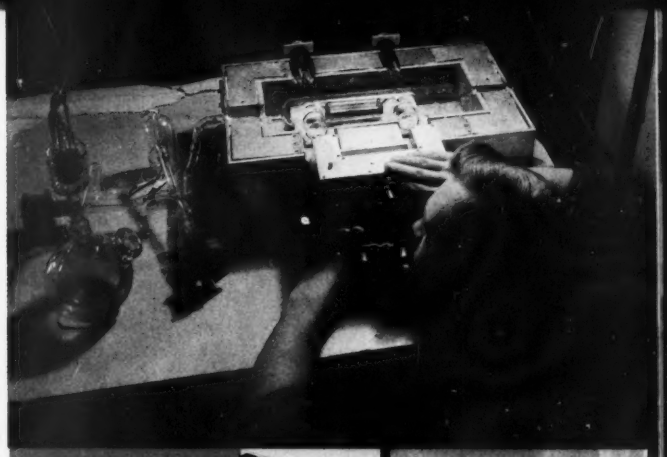

Figure 4

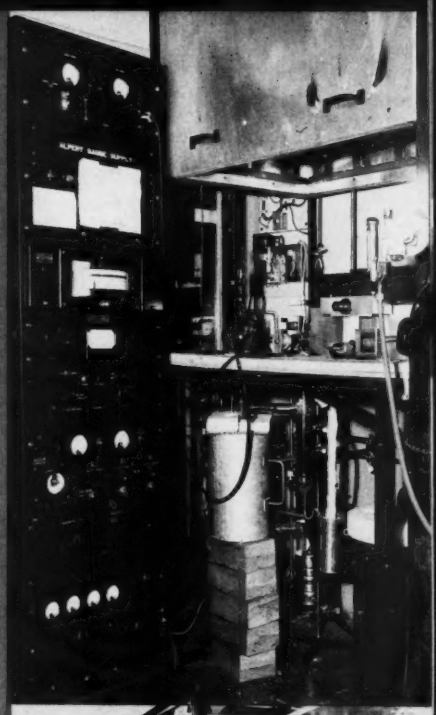

Figure 5

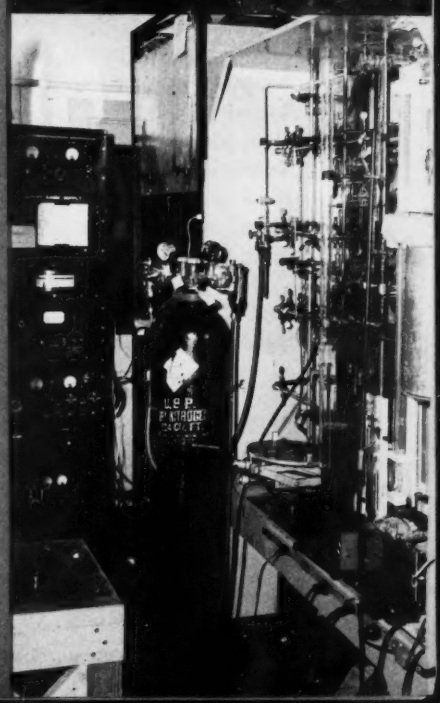

Figure 6

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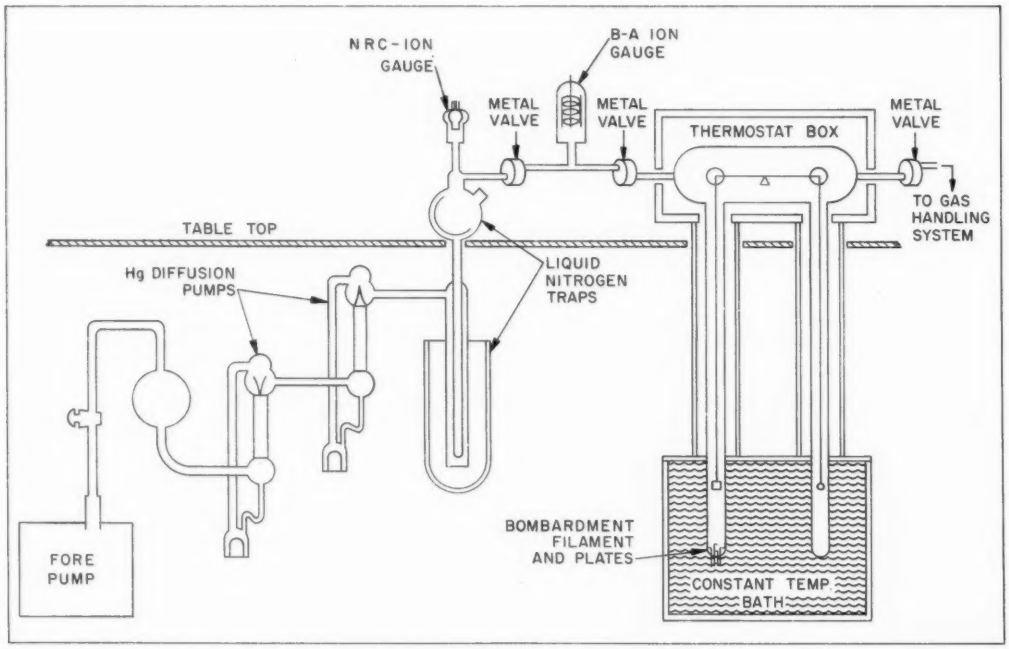

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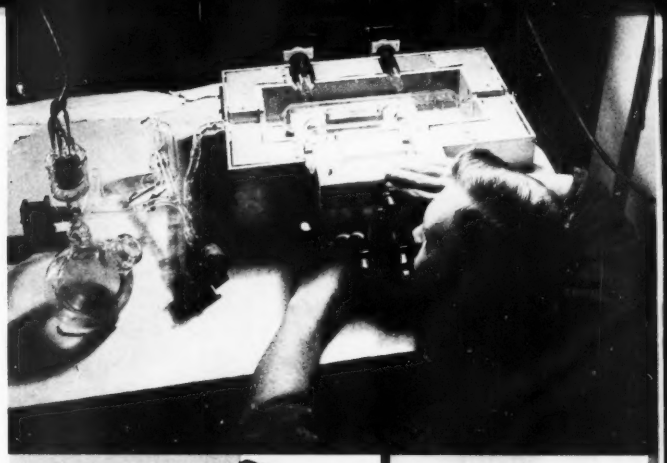


Figure 4

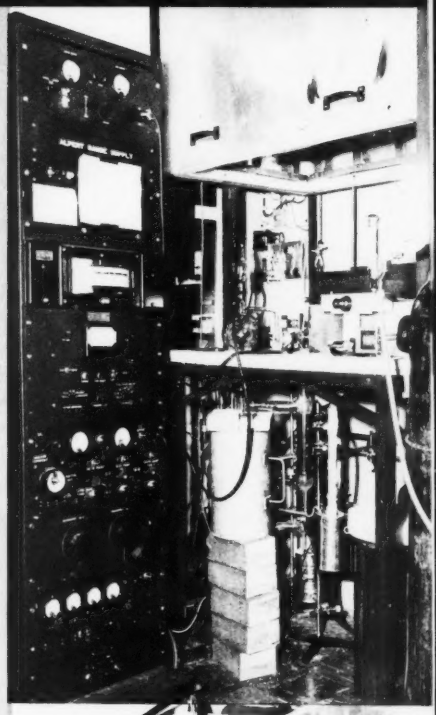


Figure 5

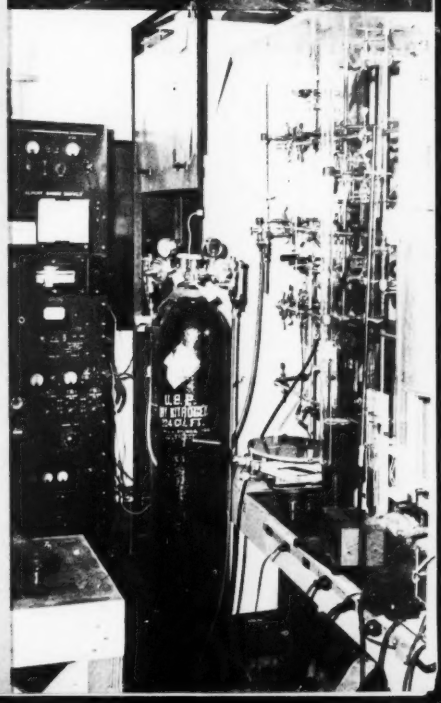


Figure 6

850 volts were placed through the balance ground connection. The balance beam was arrested during the experiments. The bombardments were at constant voltage and ion current conditions, with the ion currents being adjusted by varying the filament emission.

In order to obtain a basic understanding of semiconductor surfaces, it is necessary that the surfaces studied be atomically clean. This requires that the surface have no residual oxide or adsorbed impurities. Such surfaces may be prepared by several different methods. In the cases of germanium and silicon, the most widely used technique has been that of sputtering or physically abrading surface layers by positive ion bombardment using an inert gas such as argon. Most of the microbalance work has been with surfaces prepared in this manner.

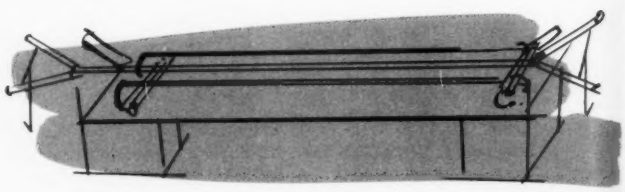
Oxidation data obtained immediately following the bombardment provide information concerning the nature of the bombarded surface. At pressures of approximately 10^{-9} mm, the adsorption of the first layer of oxygen on germanium is so slow that the kinetics of the process can be observed. From such data, it has been found that the sticking coefficient (i.e., that fraction of the total number of atoms striking a surface which are adsorbed by that surface) of oxygen on germanium is of the order of 10^{-3} at a coverage of 0.1 monolayer, decreasing to less than 10^{-4} at monolayer coverage of oxygen. Other workers using electron diffraction techniques for studying germanium surfaces have reported similar values for the sticking coefficient (S). That S for oxygen on germanium is so low (S equals 0.5 for nitrogen on tungsten) has been used by some to support the contention that ion-bombarded surfaces are not atomically clean.

One of the most interesting aspects of the surface effort has concerned the attempts to provide clean, reproducible germanium surfaces. The conventional technique of prolonged bakeout at or near the melting point of the material was not satisfactory. Surfaces prepared by crushing in vacuum, or by reduction in hydrogen or carbon monoxide, have been used; however, as mentioned earlier, the most popular and widely discussed method has been that of positive ion bombardment. The extent of cleanliness of such surfaces, however, has been the cause of considerable discussion.

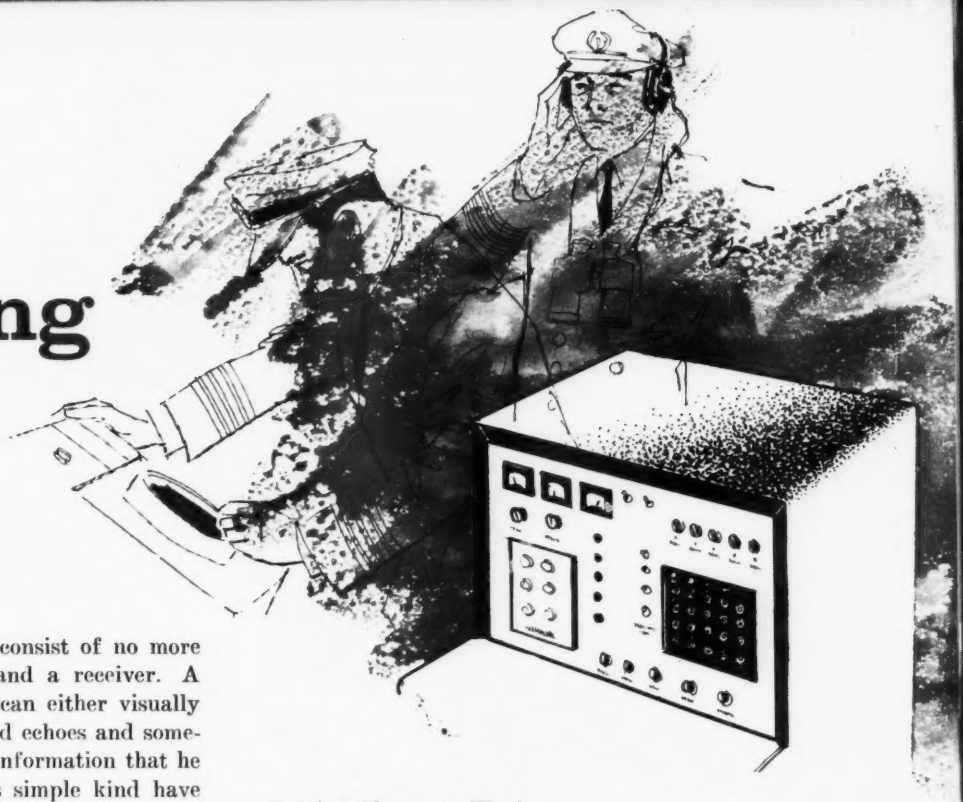
Early surface investigators reported that ion-bombarded surfaces which had been exposed to oxygen could be restored to their pre-oxygenated (clean) condition by a brief heating at 500°C. Since it is to be expected that the first chemisorbed layer of oxygen could not be so readily removed, speculation arose as to the possible causes of this thermal regeneration phenomenon. The explanations offered were: (1) The surfaces were originally covered by at least a monolayer of oxygen. Consequently, the adsorbed oxygen was very weakly bonded and could be easily removed. (2) The oxygen dissolved in the germanium on heating. Such behavior has been observed in other metal-oxygen systems. (3) The oxygen is removed as germanium oxide, which is quite volatile at 500°C. Recent work in other laboratories and with the microbalance in this laboratory indicates that the vaporization of germanium oxide is probably the significant factor; however, a temperature of 575-600°C is necessary for complete regeneration. This leaves unexplained the numerous observations at 500°C and a reported regeneration at a temperature as low as 300°C. It must be considered, however, that such observations were usually indirect, in that an electrical property such as the surface conductivity was being measured. The sensitivity of such measurements may well be much greater than that of the available adsorption techniques. The regeneration effect is still one of the most interesting, and most poorly understood, factors concerning germanium surface behavior.

As a further illustration of the usefulness of the microbalance equipment, it is worthwhile discussing briefly the presence of such impurities as oxygen in germanium crystals. During initial microbalance experiments with germanium, large pressure rises with corresponding weight losses were observed as the samples were heated. It was not possible to correlate these weight changes with the desorption of adsorbed gaseous impurities, or the vaporization of germanium or one of its oxides. Separate mass spectrographic investigations substantiated our belief that the observed changes were due to the evolution of oxygen, nitrogen, and hydrogen from the bulk material. It was only through the continuous experimental record provided by the microbalance, however, that we were able to detect the presence of these elements.

The increasing interest in high temperature semiconductor devices has stimulated research on new materials. Silicon carbide has advanced to the front for high temperature applications. The design of the vacuum microbalance system makes it possible to study such materials at temperatures in excess of 1200°C. The behavior of silicon carbide and other such materials in oxygen and other ambients are problems which will soon be of importance. The versatile microbalance equipment will fit easily into the basic research effort on high temperature materials.



radar data processing



R. L. Wyckoff
Wayland Laboratory

A primitive radar system may consist of no more than a transmitter, an antenna and a receiver. A good operator is then needed to scan either visually or aurally the entire set of received echoes and somehow translate this signal into the information that he is seeking. Radar systems of this simple kind have been carefully improved upon over the years by design engineers who created a large body of knowledge showing how to optimize such parameters as bandwidth, pulse width, antenna scan rate, antenna beam width, etc. Even with the help of all this knowledge, the radar designer was often left with a nagging doubt that he had optimized everything that was relevant to the problem. The reason for this dilemma was that the memory, acuity, and analytic ability of the human operator played a vital role in the system, and his functioning could not be systematically described and analyzed.

Information-Communication Theory Comes to Aid Designer

The radar designer began, therefore, to take notice of some important theoretical developments in the general communications field under the heading of Information Theory and Communications Theory. It was quickly seen that a radar system could be described as a noisy communications channel handling a coded signal which conveyed information. Information-communication theory bears directly upon problems of this kind. A systematic method pinpoints the theoretical limits of performance that can be expected of an ideal system. This method in principle can be applied to the radar design problem directly to specify mathematically exactly how one processes the received signal in order to produce the theoretically ideal receiver.

Putting Theory to Work

The radar designer can ensure near-ideal performance by taking careful pains to hold the signal-processing equipment strictly accountable at each stage of the process for *all* of the information embedded in the received echo signal. Since information-communication theory tells him mathematically how he ought to process the signal in order to extract all of its information content, he can break down the mathematical expression into separate operations, each of which can be performed in practice by an equivalent electronic operation. In cases where the ideal equivalent is difficult or impossible to build, he satisfies himself with an approximate equivalent whose slight departure from ideal performance can be estimated.

The first real application of communication theory to radar problems at Raytheon occurred when we began building radars which sorted out targets in the radial velocity domain as well as the range domain. The Moving Target Indicator (MTI) radars were hailed as being quite remarkable because they completely rejected fixed targets. From the communications theory point of view, however, this is a triviality. If moving target signals are separable from stationary target signals (and they always have been), and if it is desired to see only moving targets, then the ideal signal processing equipment indeed should possess some sort of a filter which passes only moving target signals.

A good basic radar system in which a human operator performs the data processing. For many applications this system is near-ideal from the Information-Communication Theory point of view.

Matched Filters and the Decision Process

One basic information-communications problem to be solved in the radar field concerns the recovery of information from a signal contaminated with a known amount of receiver noise.

It has been made fairly clear recently in the literature of communication theory that in order to maximize the sensitivity of a receiver-detector for a particular waveform $s(t)$, where the interfering background is white noise, one can do no better than build an equipment which correlates the expected waveform with the waveform received. This is called cross-correlation. If the received signal-plus-noise is $f(t)$, and if the allowable observation time is T, it will be found that the cross-correlation is described mathematically by the integral

$$f_o(T) = \int_o^T f(t)\ s(t)\ dt\ .$$

Ordinarily, T is the time-on-target afforded by the scanning antenna beam.

A study of this expression does not always suggest to the equipment designer any particularly convenient method of instrumenting this process for certain forms of $s(t)$. It is possible, however, to transform this expression from a time function to a frequency function. This transformed expression suggests the use of a filter whose impulse response is a mirror image of the expected signal $s(t)$ — from whence comes the term *matched-filter*. Since the use of a matched-filter is mathematically equivalent to cross-correlation, we may expect to use these concepts interchangeably as needed to discuss the ideal receiver in either the frequency domain or the time domain. Before applying the matched-filter concept to the problem of what to build for a radar receiver, one must be certain that it applies, since the matched-filter guarantees only to maximize α, the ratio of the response-to-signal to the response-to-noise. The maximum possible value of this ratio is

$$\alpha_{max} = \frac{\text{signal energy}}{\text{noise power per cycle per second}} = \frac{E}{N_o}\ .$$

The proof of applicability to the detection of a radar signal has been made by many workers in the field and the results are all we could hope for. This filtered signal may now be connected directly to other kinds of amplitude-sensitive devices. Whichever of these devices is used, the use of a matched-filter ahead of it guarantees that the presence or absence of signals against a noise background may be announced with a minimum cost in terms of decision errors.

The output of the matched-filter may be used in various ways as mentioned, but in a search radar they all reduce to comparing its output with some threshold value. One might place the threshold low and cause the radar to make a large number of decision errors in the form of false alarms — announcing the presence of a signal when none was there. One might also place the threshold high, causing decision errors in the form of signal misses. Somewhere in between is the proper threshold value which minimizes in some sense the total price paid for both kinds of error.

If external noise (atmospheric, cosmic, or man-made) is significantly greater than receiver noise (as is often the case), a new problem arises — determining the characteristics of the noise and its amount. If this external noise is white and is measurable, the foregoing analysis is still valid, but complications are necessarily added to the equipment. Now the equipment must somehow be adjusted to an environment in which the external noise is usually changing with time. Perhaps the ultimate in an automatic system is one in which external noise is constantly evaluated and the threshold is constantly readjusted to provide constant false alarm rate behavior.

Applying Matched-Filter Concept to Radar Design

The engineer who applies the matched-filter concept to radar design problems finds at once that since the

signal he is seeking is an echo, he has an important advantage in that he knows in advance many attributes of the signal s(t) that he is trying to detect. Except for a shift in the time domain, a shift in the frequency domain, and a reduction in amplitude, every desired radar received signal is (very nearly) a replica of the transmitted signal. Indeed, it could be said that the sole job of the radar signal processing equipment is to measure these unknown shifts. When it has done so, the radar has extracted from the received signal all of the information that it contained. The time shift is a measure of the distance to the reflecting object being sought, the frequency shift is a measure of the radial velocity of the reflecting object and the amplitude is (in some cases) a useful, though inaccurate, measure of its size and characteristics. (Radars employing extremely short pulses may observe break-up of the target return because of separate reflection from wings, tail, fuselage, etc. This poses additional problems, which are outside the scope of the present discussion.)

The important general results of an analysis of any search-radar receiver design probe may be listed as follows:

1) The theoretically ideal receiver should contain a "matched-filter" for *each different* (resolvable) expected received signal. These filters will always be linear filters.
2) The output levels of these filters should each be repeatedly or continuously compared to some threshold level; with the presence of a signal being announced whenever the threshold is exceeded.
3) The radar will make decision errors due to the presence of background noise and random signal amplitude fluctuations. The frequency of these errors may be controlled by manipulating the threshold comparison level.

The above-mentioned need to provide in an ideal radar a separate matched-filter for each possible received signal has been most often dealt with by time-sharing or consolidation in various ways. Irrelevant parameters, as perhaps the amplitude of the return, must be averaged over in some way. The useful information-carrying dimensions in the radar signal "space" include (1) azimuth, (2) elevation, (3) radial distance, and (4) radial velocity. Most search radar antennas are single channel devices which can look in only one direction at a time, and they are usually rotated continuously in azimuth, spending only a limited time looking for any particular target. The entire set of resolvable azimuth channels at the radar are thus provided by simple time-sharing. It often happens that the elevation dimension is covered by fanning out the single antenna beamwidth in the vertical direction so that time-sharing is not needed to cover this dimension. The radial distance dimension is often dealt with by taking advantage of the natural time-shared characteristic inherent in the pulse radar signal itself.

With respect to the first three dimensions of the signal space just discussed, nothing has been mentioned which would be news to the designer who was building radars before communication theory and statistical decision theory arrived on the scene. The fourth dimension, radial velocity, has been rather neglected by many radar designers, until recently. In the received signals of most pulse radars there is a large number of separately resolvable positions in the frequency domain which could contain a doppler-shifted echo. Too often, however, the radar designer has allocated only one channel to cover the entire frequency (radial velocity) span of this important dimension of the signal space.

As brute force methods of improving radar performance approach the limit of the state of the art, the designer is compelled to make maximum use of all of the information content of a radar signal. Modern, sophisticated radar designs, therefore, are usually found to contain the extra equipment necessary to sort the received signal in the doppler-frequency domain, thus looking for each received signal against as small a noise background as possible. It is the high cost of building these sophisticated radar signal processors that has forced the designer to proceed cautiously, backing up his designs with careful application of the latest theories. When his analysis discloses mathematically what the ideal receiver for his radar set *must* do, then it is possible for him to proceed confidently to build the electronic equivalent to the mathematical "model," knowing that nobody could improve upon the performance of this ideal receiver by employing some trick circuits or short cuts not yet invented.

The mathematical model for an ideal receiver is based upon the important parameters of the particular (1) transmitted signal, (2) antenna, and (3) end use of the whole radar system. It is not possible here to go into the reasons for selecting a particular transmitter waveform or antenna; indeed, this whole subject is poorly defined because no two persons or agencies can agree on the particular complex optimizing criterion which should be applied to the problem. The important thing to note, however, is that as soon as the transmitter signal, the antenna, the reflecting characteristics of the target, and the external noise sources are specified, then T and the probability distribution of s(t) become known and one can describe mathematically the matched filter(s) which must comprise the ideal receiver. The relevant parameters include the following:

pulse width
pulse repetition frequency
transmitter carrier frequency
time on target (function of antenna beamwidth and rotation rate)
desired target range coverage
desired target radial velocity coverage
permissible random false alarm rate
permissible missed target rate (for targets of specified size).

When the designer completes the mathematical description of the ideal receiver based upon these known parameters, and when he has determined, piecewise, how closely he is able to (or wants to) electrically duplicate this mathematical model, then he is ready to calculate how much transmitted power he must use in order to ensure adequate received E/N_o from the smallest, most distant target that must be detected.

Some Mathematically Useful Electronic Processes

The engineer who instruments electronically the matched-filters called for by his mathematical analysis of the radar receiver design problem will employ many kinds of circuits whose performances come measurably close to matching a mathematical operation. A number of these circuits will be mentioned here and associated with their mathematical equivalents.

Modulation is most often used to shift the received signal to a different place in the frequency spectrum, where the signal is more convenient to handle. A modulator multiplies two functions of time. The frequency spectrum of the output of an ideal modulator should be the convolution of the two input spectra. Mathematically, multiplication in the time domain corresponds to convolution in the frequency domain, and vice-versa. The convolution of two time functions $f_1(t)$ and $f_2(t)$ is expressed by the integral

$$\int_{-\infty}^{\infty} f_1(\theta)\ f_2(t-\theta)\ d\theta\ .$$

Non-ideal properties of a real modulator take the form of spurious frequencies in the output spectrum such as noise, input-output feedthrough, harmonics, and intermodulation distortion.

Sampling or *gating* describes a special form of modulation performed upon a received signal by a time function which is discontinuous, having a value of zero except during the sampling or gating intervals. Mathematically, it is still a multiplication of two time functions. When used in the form of a range gate in a pulse radar, this process is the first step in carrying out electronically the cross-correlation function mentioned earlier.

The common process called filtering is to the frequency domain what modulation is to the time domain. Filtering, too, is a multiplicative process in which the output of a filter has a spectrum which is the product of the input spectrum times the filter's frequency response. It can also be said that the output of a filter is a time function which is the convolution of the input waveform with the impulse time response of the filter. The most important non-ideal property of passive filters as a class lies in the fact that they may not always be synthesized to conform completely to a desired characteristic without being hopelessly

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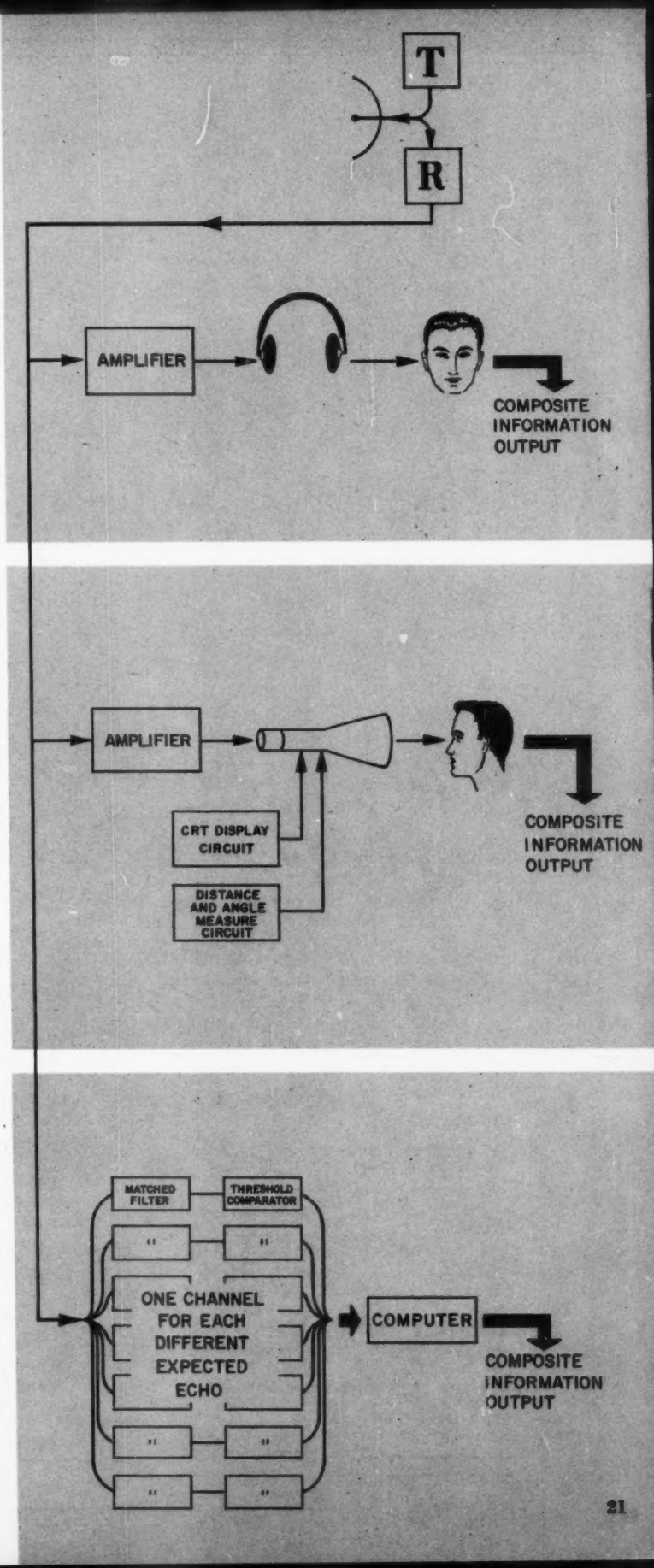
complex or lossy. *Delay lines with feedback* comprise an interesting special class of active filters which operate in the time domain to provide frequency responses which are characterized by their cyclic behavior. For example, with a delay line and positive feedback one may build a matched filter for a burst of evenly spaced pulses. The application to pulse radar receiver design is obvious. The equivalent passive filter to perform this job would be impractical to construct. This is but one example of how fruitful it can be for the designer to think freely in either the frequency domain or the time domain when seeking the solution to his ideal receiver design.

Rectification or *envelope tracing* is a familiar operation which is used typically to produce a signal representative of the instantaneous power contained in a signal whose frequency spectrum does not include zero. In practice, some post-detection integration (smoothing-filtering) is usually performed, even if only to get rid of the original waveform and the unwanted distortion products created by the non-linear rectifier. When this smoothing takes the form of peak-detection, we call the entire operation envelope-tracing (since that is what the output waveform appears to do).

Because a true square-law device is mathematically ideal for measuring power, much of the literature on the subject of "detectors" is written assuming the use of one; however, the "linear" diode detector provides a nearly equivalent performance. That is the reason for the rather loose talk about one or the other interchangeably, depending upon convenience.

New Data-Processing Components Needed

Today's designers of radar receivers are in a good position to advance significantly the state of their art. As suggested in an earlier paragraph, the cost of obtaining more performance from a radar by increasing an already high transmitter power or antenna gain may be so prohibitive that the only direction of improvement left open may be in the receiver-detector system. The best possible set of matched-filters and detectors which would comprise the ideal receiver has never been built. Compromises have always been made in the interests of cost, size, and complexity. Cheaper, smaller and simpler components and circuits are needed to build the large sets of matched-filters and detectors which surely must be used in tomorrow's vast radar networks. Perhaps a not too far-fetched analogue of the ultimate in what we are seeking may be the arrays of rods and cones in the human eye. These are, at one and the same time, filters, amplifiers and detectors of electromagnetic radiation and serve information to the most complex data-processing network of them all.



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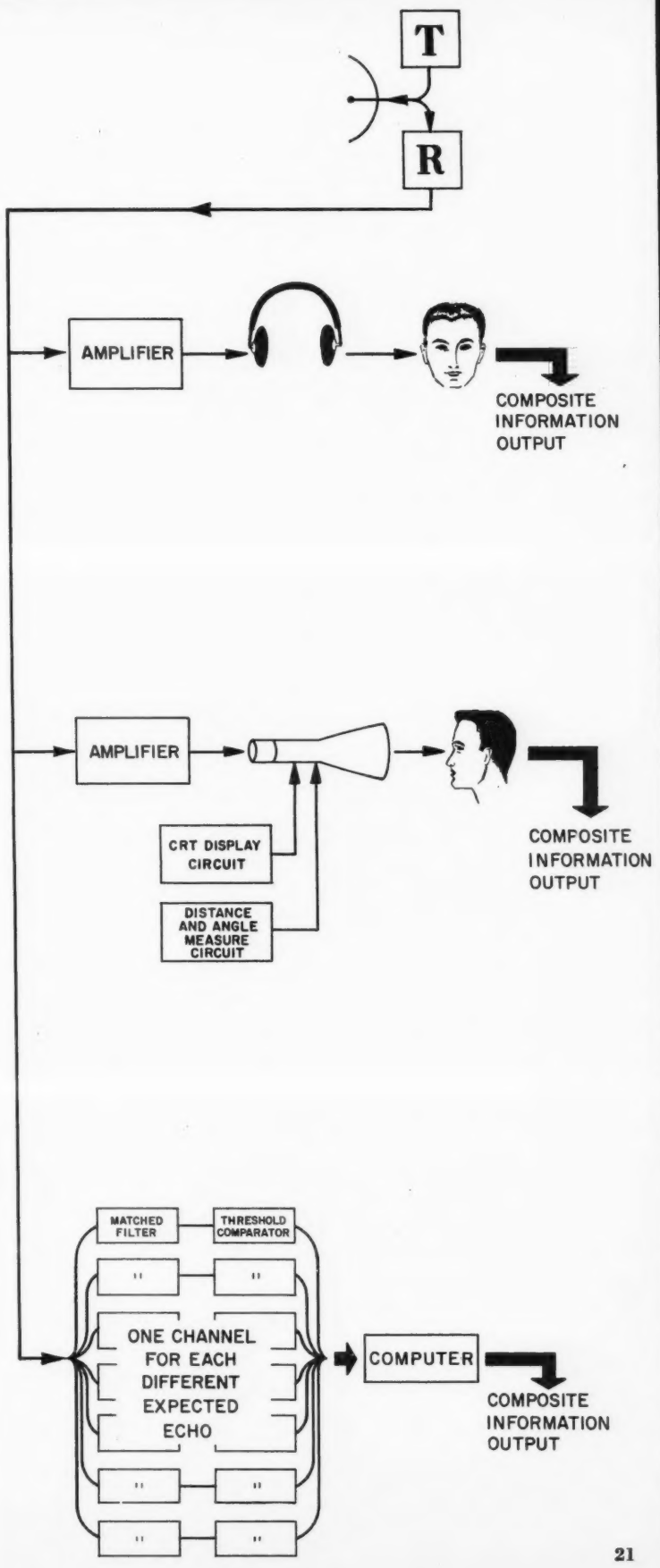
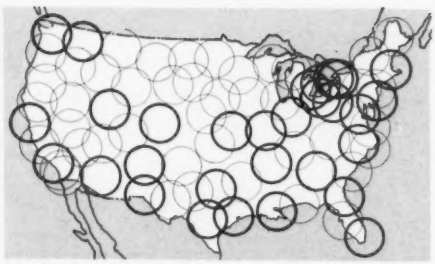


A Raytheon Flight-Tracker radar mounted on a 75-ft. tower at Indianapolis Municipal Airport keeps an electronic eye on airlanes.

NEW LANDMARKS OF THE JET AGE

Raytheon air traffic radars operating at U. S. airports



To date 26 Raytheon Flight-Tracker radars have been delivered to the C.A.A. for installation at the heavily circled areas. By mid-summer 1959 these long-range units will be installed at a total of 33 airports as part of a nationwide air traffic control network. Light circles indicate future coverage.

Now on the job, the first Raytheon Flight-Tracker radars are already safeguarding commercial and military aircraft. A total of 26 installations will soon be commissioned and linked in a nationwide system of air traffic control.

Flight-Tracker radars work to relieve airlane congestion, reduce stacking, speed schedules. Engineered and produced by Raytheon for the Civil Aeronautics Administration, this new equipment detects and tracks planes—even supersonic jets—day and night, in any weather. It "sees" 4-engine transports up to 200 miles away, at altitudes up to 70,000 feet.

By giving the Jet Age "more sky to fly in", Raytheon radars are contributing to U.S. air transportation progress.

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RAYTHEON MANUFACTURING COMPANY, WALTHAM, MASS.